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FEASIBILITY OF A DIRECT CONTACT HEAT AND EMISSION LOSS PREVENTION SYSTEM FOR AREA SOURCE FURNACES

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FOREWORD

This document examines the feasibility of a Heat and Emission Loss Prevention System (HELPS) for area source furnaces. This goal can be accomplished by the continuation of the theoretical analysis contained in this report with a laboratory test program.

This study was performed for the Environmental Protection Agency, Research Triangle Park, North Carolina. Mr. Walt Steen was the EPA Task Officer. The Aerotherm Program Manager was Dr. Kim Clark. Acting as Technical Advisors for the task were Mr. J. E. Ferrell, Dr. C. B. Moyer, and Mr. R. A. Brown. The study was performed during the months of August to November 1975.

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SECTION 1

EXECUTIVE SUMMARY

1.1 INTRODUCTION

The major objective of this report is to describe a unique method of reducing both air pollution emissions from, and energy consumption of, furnaces used for residential heating. The method proposed consists of a post-combustion control device utilizing the direct contact, or wet scrubbing, concept. A simple, lab-scale test facility to investigate the feasibility of the device is also described in this report.

The objective of the study is accomplished by the following report subsections:

- Heating for the Residential Section, in which the types of heating equipment and their population breakdown is discussed. Their air pollutant emissions and energy use are also characterized.
- Emission Reduction and Energy Conservation Methods, which discusses the historical, presently used, and proposed methods of accomplishing these two goals for residential heating equipment.
- The HELPS Concept. The acronym stands for Heat and Emission Loss Prevention System, and this section of the report describes the concept's inception, and the benefits and costs of the proposed direct contact device for simultaneous heat and emissions recovery from the flue gases.
- The HELPS Test Program, which describes the design, operation, and costs of a lab-scale test facility involving the retrofit of a direct contact device to a typical domestic, oil-fired, warm air furnace.
- Conclusions and Recommendations, in which the study's major findings are summarized and recommendations are given for achieving the goals of the HELPS program.

In all, the report develops a clear picture of the opportunity for emission reduction and energy conservation for residential furnaces by application of a direct contact device.

The remainder of this section consists of brief summaries of the texts of Sections 2 through 7 of this report.

1.2 HEATING FOR THE RESIDENTIAL SECTOR

The broad size ranges in terms of heat release rate generally used by the EPA for residential, commercial, and industrial furnaces and boilers are:

Residential:	Up to 3×10^5 Btu/hr
Commercial:	3×10^5 Btu/hr to 10.5×10^6 Btu/hr
Industrial:	10.5×10^6 Btu/hr to 500×10^6 Btu/hr

This report focuses on equipment used in the residential sector.

The two most common types of residential heating equipment utilizing the in situ burning of a fuel are forced warm air furnaces and hydronic systems. The remaining equipment types are rare and include such designs as floor, wall, or pipeless. The present study treats only warm-air furnaces and hydronic systems.

A warm air furnace is a self-enclosed appliance used for heating air for a house or building. The furnace consists of a burner with related piping and controls, a heat exchanger, and a blower for forced air systems. Furnaces are fired by natural gas and distillate oil. The combustion takes place in the primary combustion space of a metal-walled heat exchanger. The air to be heated circulates over the outside of the heat exchanger and then is expelled into the space to be heated at 100°F to 150°F, while the combustion products, at 400°F to 700°F, pass through a flue to the atmosphere. Domestic warm air furnaces are classified into four types: upflow, downflow, horizontal, and "basement." They differ only in the relative positions of the blower and heat exchanger and the outside shell dimensions.

The other major type of residential heating system utilizes the hydronic boiler. These units generally have heat exchangers constructed of vertical sections of cast iron. Water enters at the bottom of the sections and hot water or steam exits at the top. The products of combustion are conducted through labyrinth passages cast into the sections. Cast iron boilers are available in either gas- or oil-fired designs, and are more expensive than their counterpart warm air furnaces.

Data from the 1970 U.S. Census indicate that gas-fired forced warm air furnaces are the most prevalent type of heating system, with 32 percent of the total. Ranking second at 12 percent are oil-fired hydronic systems (found mostly in the Northeast), followed by oil-fired warm air furnaces. In addition, the Gas Appliance Manufacturers Association (GAMA) data show that the nationwide trend

is toward gas-fired warm air furnaces. Clearly, a program involving the retrofit of a direct contact heat and emissions recovery system should, at the least, focus on warm air furnaces.

In all, natural gas and distillate oil-fired heating equipment account for 80 percent of the residential heating units in the U.S. The actual contribution from fuel combustion in this equipment to the total national air pollutant loading (summation of mass of particulate, SO_x, NO_x, CO, and unburned hydrocarbons) is unclear. From all indications, however, this contribution probably falls in the 1 percent to 10 percent range. This impact on air quality was deemed sufficiently significant that the EPA has initiated an emission reduction R&D program. In addition, residential space heating represents about 11 percent of the total U.S. energy consumption. It is obvious that there would be significant advantages to reducing both emissions and energy consumption, the stated goal of the proposed HELPS program.

1.3 EMISSION REDUCTION AND ENERGY CONSERVATION METHODS

Methods for reducing emissions from residential furnaces can be modeled after those used successfully on larger units, such as utility boilers. These methods fall into three basic categories: pre-combustion, post-combustion, and combustion control methods. The fuel switching operation dictated by the first strategy is impractical and costly. Combustion control methods consist mainly of burner maintenance, tuning, and improved burner deisgn. These strategies have been quite successful, but it has been shown in many cases that emissions of oxides of nitrogen increase with tuning for optimal thermal efficiency. Tuning is, in any case, limited in scope due to the crude and simple burner designs found in residential furnaces.

Post-combustion control methods for residential furnaces have not yet been investigated. These include such devices as spray and packed towers, filters, electrostatic precipitators, and cyclones. The latter three are not well suited for the type of fine particulate generated by an oil-fired residential furnace and would be useless on a gas-fired furnace. Wet devices such as the spray and packed towers have the potential for removing both particulate and gaseous emissions.

The number of studies concerned with emission reduction is far outweighed by the number aimed at reducing energy consumption in the residential sector. These efforts are being led by both government and industry. The objective of these programs, like the two major energy conservation strategies themselves, can be divided into two basic categories:

- Reduce energy consumption by architectural modification
- Reduce energy consumption by alteration of the energy conversion system.

The present study concentrate on the latter strategy.

Modification of the energy conversion system, or furnace in this case, can be accomplished by changing the combustion equipment (i.e., burner and combustion chamber), new heat exchanger design, closing the flue during the off-cycle, and recovering heat from the flue gas. The latter method affords the greatest benefits. If both latent and sensible heat are recovered from the flue gas, an energy savings of 28 percent will result. Recovering latent heat dictates, however, that the device be a condensing heat exchanger.

The device described in Section 5 of the present report will meet this requirement. The wet scrubber concept will cool the flue gas far below the condensation point to ensure maximum heat recovery. In addition, the goals of the HELPS program, that of concurrent heat and emission recovery, can be achieved at least conceptually by choosing a direct contact device.

1.4 THE HELPS CONCEPT

The HELPS concept involves the retrofit of a small wet scrubber in the flue of oil-dired residential furnaces. The device would be cylindrical in shape (D = 1 ft, H = 1.5 ft), be fabricated from economical PVC plastic, and include spray nozzles, a chevron demister, packing material (in the case of the packed tower concept), and I.D. fan, and related piping and controls. Table 1-1 gives the HELPS device design and performance characteristics.

Calculations show that the device can recover 84 percent of the heat from 500°F flue gas, bringing the overall furnace system efficiency up from 80 percent to almost 97 percent. Applied to most oil-fired residential furnaces, the HELPS device will achieve a 10 percent reduction in the national consumption of distillate oil, which is equivalent to a 1 percent reduction in the Nation's gross energy consumption. Reducing demand for heating oil frees this clean fuel for other, perhaps more cost-effective uses. Alternately, energy and money can be saved in refinery operations by lowering the production of energy-intensive, expensive distillate oils.

In addition to the energy savings, the device will capture 90 to 95 percent of particulate over 1μ by weight, and virtually 100 percent of the NO_2, SO_3, and unburned hydrocarbon emissions. Although the impact on reducing the nationwide production of these pollutants is small, it is felt that reducing emissions from those oil-fired residential furnaces located in densely populated cities will afford added leverage for the attainment or maintenance of the NAAQS.

The capital cost of the HELPS device, including installation charges, is estimated at $225. This is the retail cost to the homeowner of a mass-produced item. Additional costs

TABLE 1-1. HELPS DEVICE DESIGN AND PERFORMANCE CHARACTERISTICS

General shape	Cylindrical
Operational principle	Spray and packed tower
Height	18"
Diameter	10"
Materials of construction (production item)	PVC plastic
Scrubbing water flowrate	0.5 GPM (0.05 GPM makeup)
Scrubbing water inlet temperature and pressure	50°F, 40 psig
Scrubbing water outlet temperature	120°F
Flue gas inlet temperature	500°F
Flue gas outlet temperature	80°F
Flue gas enthalpy	20,650 Btu/hr
Heat recovered	17,350 Btu/hr
I.D. fan power (1/8 hp)	320 Btu/hr
Net heat recovered	17,030 Btu/hr (84%)
Overall furnace system efficiency	~97%
Pollutant removal efficiency:	
Particulate	90-95% over 1μ (by weight)
NO_2, SO_3, HC	~90%
CO, NO, SO_x	~0%

for water and electricity amount to a total of $19 per year, while $5 is an estimated maintenance cost. The total annual operating and maintenance cost, therefore, is the sum of these costs, or $24.

Due to the rapidly varying cost of energy, calculating a payback period based on a single figure for fuel oil cost cannot be justified. More reasonably, a range of payback time versus fuel cost must be defined. Figure 1-1 shows how the time required to break even on the cost of the HELPS device varies with fuel cost. In any case, the attractiveness of the HELPS device for energy recovery is directly proportional to fuel cost, for which an increasing trend is predicted.

It must be remembered that the foregoing emission reduction, energy conservation, and cost figures associated with the HELPS device were estimates based on the design and performance of larger scrubbers. The actual benefits and costs to the nation of the HELPS device can be determined only through a laboratory investigation such as that outlined in the following section of this report.

1.5 THE HELPS TEST PROGRAM

The analysis done previously has proven the theoretical feasibility of using a wet scrubber for concurrently cleaning and recovering heat from the exhaust of a residential furnace. However, the many unknown operational factors associated with the HELPS device must be determined empirically. It is suggested, therefore, that a laboratory investigation be initiated using a typical residential furnace, a prototype HELPS device, and all necessary instrumentation and support equipment.

The laboratory set-up, shown in Figure 1-2, will be simple to construct and operate. Sensors and measurement instrumentation will obtain energy and emissions data from the furnace and the candidate HELPS device. Much of the required support equipment, most notably the emissions analyzers, already exist in Aerotherm's Combustion Research Laboratory and will be available for use in the HELPS program. Besides being very simple in concept, the proposed facility is devoid of compromising scale-up difficulties; the HELPS device will be tested on the exhaust from a full-size combustion device.

Aerotherm recommends a program divided into eight tasks as most appropriate to accomplish the objectives of the program. They are:

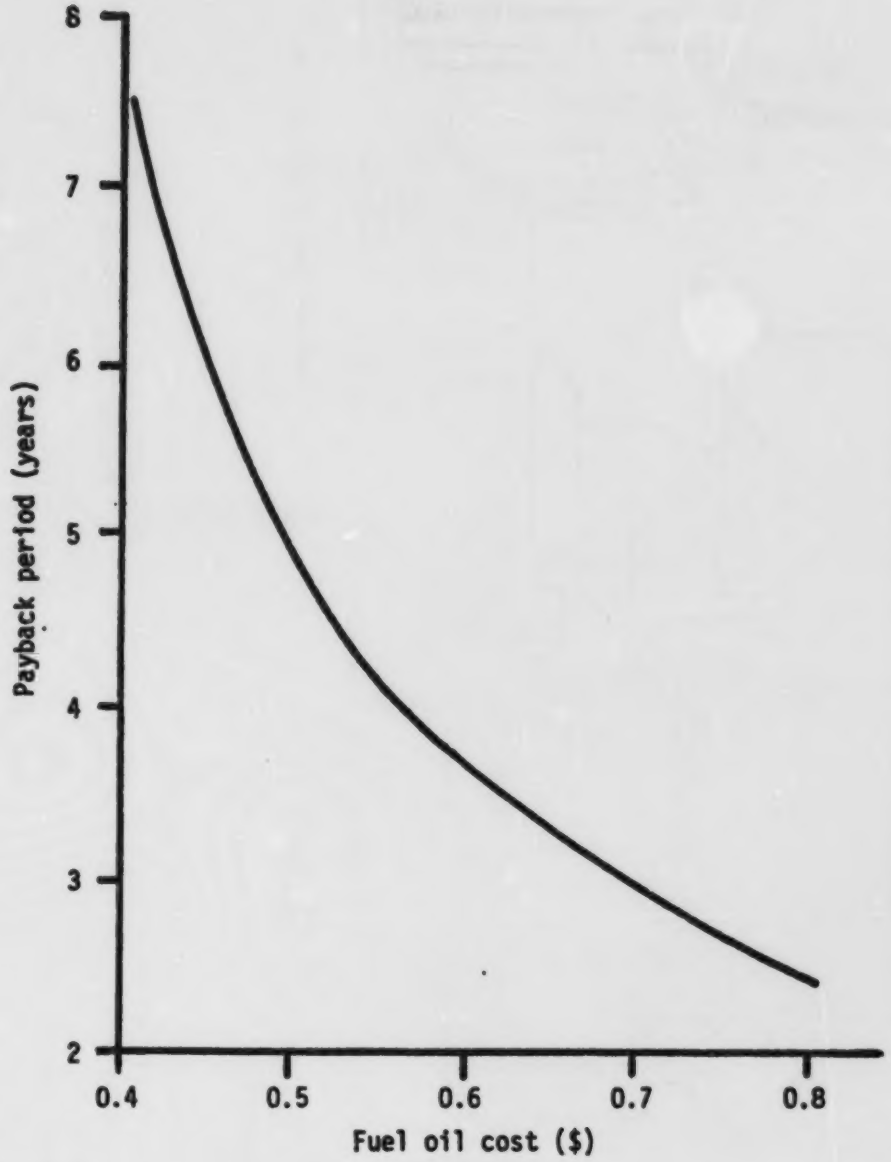
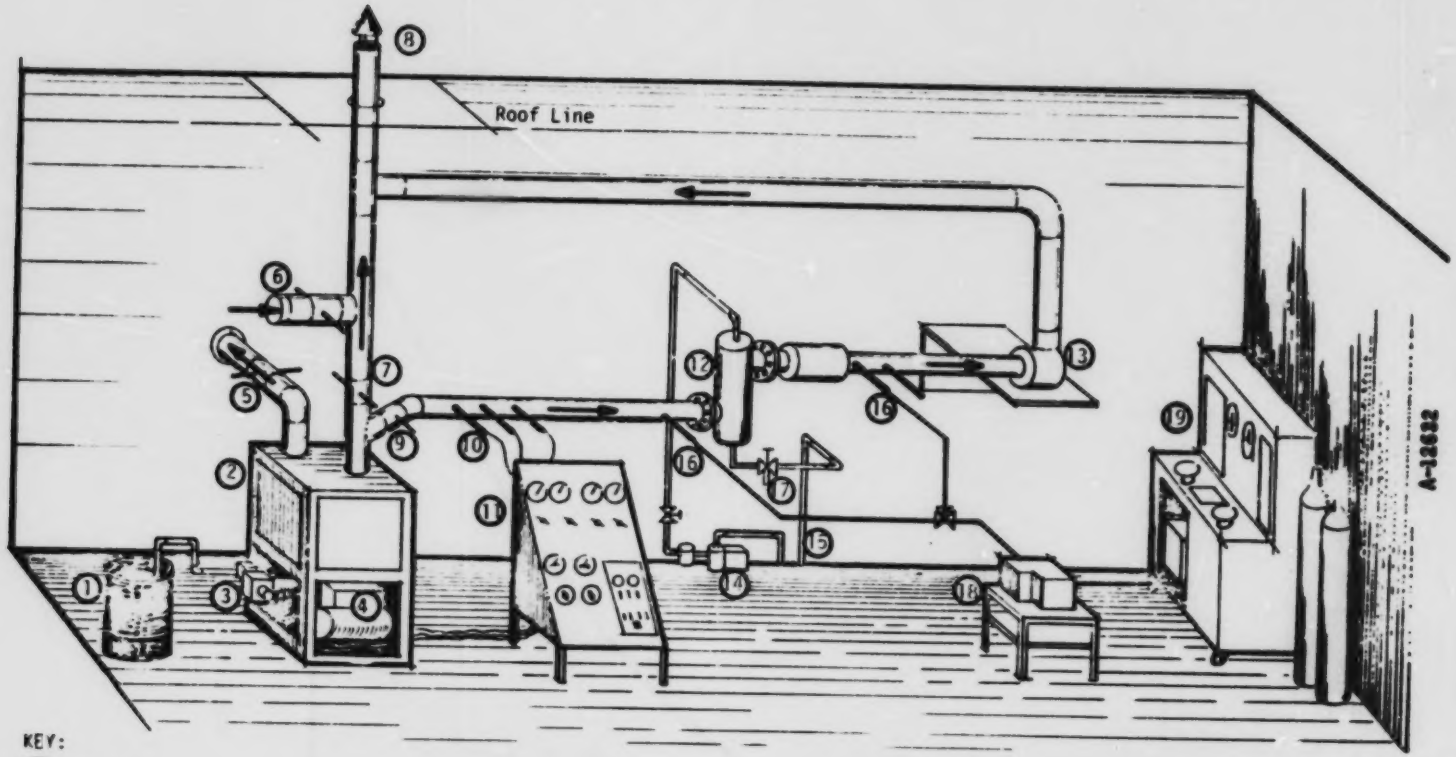


Figure 1-1. Payback period versus fuel oil cost.



KEY:

1. Oil Drum
2. Furnace
3. Furnace Oil Burner
4. Furnace Blower
5. Warm Air Outlet Butterfly Valve (Exhaust No. 3)
6. Draft Controller Butterfly Valve
7. Exhaust Leg Butterfly Valve
8. Flue (Exhaust No. 2)
9. HELPS Leg Butterfly Valve
10. Sensors (Thermocouples, Pitot Tubes, etc.)
11. Control Board
12. HELPS Device
13. Induced Draft Fan
14. Water Pump
15. Water Drain
16. Emissions Sampling Probe
17. Water Sample Drain
18. Emission Sample Conditioner
19. Emission Sample Analysis Bench

Figure 1-2. HELPS test facility.

- Materials procurement
- Fabrication of HELPS device
- Furnace installation
- Furnace baseline testing
- HELPS device shakedown testing
- Operational testing
- Data reduction and evaluation
- Reporting – interim and final report

The duration of the program will be 6 months.

Some of the required hardware will be supplied by Aerotherm; an additional quantity, costing about $3,700, will have to be purchased to complete the test rig. A total of 2,500 man-hours of combined engineering, technician, and technical publication personnel will be required.

1.6 CONCLUSIONS AND RECOMMENDATIONS

This document has described a proposed technique for simultaneously reducing air pollutant emissions from, and energy consumption of, residential furnaces. This method consists of a direct contact device, or wet scrubber, that is installed in the furnace's flue pipe. The water that is sprayed on the exhaust gas will collect both particulate and soluble combustion products, as well as recovering most of the heat in the flue gas thereby effectively increasing the efficiency of the furnace system. This concept is abbreviated HELPS, which stands for Heat and Emission Loss Prevention System.

Besides characterizing the residential heating sector in general and residential heating equipment in particular, this study quantitatively defines the theoretical heat and emission recovery capability of the HELPS device. In addition, estimates of the HELPS device's cost to the homeowner, as well as its payback period, were made.

The following are the study's major conclusions:

- The air pollution emissions and energy consumption of equipment used for residential heating are substantial enough that research and development programs aimed at their reduction are fully justified. Many methods have already been explored, but post-

combustion control devices have largely been ignored. Techniques capable of concurrently achieving both the energy and emissions goals, such as the HELPS concept, require investigation.

- Residential warm air furnaces are available in both gas- and oil-fired models. Since particulate is emitted only from the latter type, the HELPS device should initially be applied only to oil-fired furnaces in the U.S. When the heat recovery benefits are established on a practical basis, the device may later be applied to gas-fired units.
- Theoretically, the concept will recover most of the waste heat in the flue gas and greatly increase the efficiency of the furnace. On this basis alone, the HELPS concept appears feasible.
- Although the HELPS device will not substantially reduce air pollutant emissions on a nationwide basis, the reduction impact on local, seasonably adjusted emissions could be significant. Controlling emissions from those oil-fired residential furnaces located in densely populated cities will afford added leverage for AQCR's attempting to attain or maintain the National Ambient Air Quality Standards. In addition, most of the emissions from residential furnaces are emitted during only six months of cold weather, a factor which tends to increase the importance of reductions of any magnitude.
- The feasibility of the HELPS device on a cost basis will depend mainly on the cost of fuel oil. As the latter increases, the time required for the homeowner to recover his investment in the device decreases. Given the current trends in the economics of energy supply, the future of the HELPS concept appears favorable.

Based on these facts, the following recommendations can be made:

- The magnitude of the increase in furnace system efficiency depends not only on the performance of the HELPS device itself, but also on the method of using the heat recovered by the scrubbing water. This latter topic must be investigated before the feasibility of the system can be established.
- The effectiveness of the candidate HELPS device on emission cleanup and energy recovery, as well as its retail cost, were calculated and/or estimated by methods based on the design and performance of larger scrubbers. The actual cost-effectiveness of the HELPS device should be determined by prototype development.

- Both of the preceding recommendations can be followed by carrying out the laboratory test program outlined previously in this report. The program is simple in concept, inexpensive, and success-oriented. Completion of this project will be a major step toward determining the feasibility of the HELPS concept.

SECTION 2

INTRODUCTION

Industrial society currently needs to increase the energy supply while preventing any further degradation of the natural environment. Since most energy conversion systems produce undesirable by-products, improved techniques for abating these by-products, or pollutants, must continually be produced. For fossil fueled combustion systems, the simultaneous increase in system efficiency and decrease in harmful exhaust emissions are the major objectives of on-going research and development activities.

Furnaces used for residential heating represent a very common class of combustion system in the United States today. Heating for the residential sector accounts for almost 10 percent of the nation's energy consumption and contributes about 5 percent of the total air pollution. Identifying a method of reducing these figures is the objective of this report.

Economic factors limit design practice to small variations within two basic furnace designs: forced warm air and hydronic. This high degree of standardization enhances the attractiveness of a technique for simultaneously reducing emissions and energy consumption because it would be applicable to almost all of the 40 million units in the United States today. Such a technique is worthy of closer investigation.

Recognizing the substantial benefits of concurrent reduction in energy consumption and emissions from residential furnaces, researchers of the United States Environmental Protection Agency in Research Triangle Park, North Carolina initiated an investigation into this subject by contracting with the Aerotherm Division of Acurex Corporation to perform a broad-based study of energy consumption and air pollution associated with the residential sector and to define ways of reducing both. This study was completed late in 1974. The ensuing report identified flue gas heat recovery as affording the greatest energy conservation benefits (Reference 1). The report stated that a small wet scrubbing device installed in the flue duct would act to recover the waste heat and would capture gaseous and particulate air pollutants.

The EPA deemed the characteristics of this proposed heat and emission loss prevention system, abbreviated HELPS, sufficiently promising that the present study was authorized to take a closer look at the technical and economic feasibility of the HELPS concept. This report describes the study's findings by covering the following topics:

- A review of the equipment types, energy consumption, and emissions associated with the residential heating sector.
- An introduction of the options for reducing energy consumption and emissions in residential furnaces.
- A definition of the suggested HELPS device in terms of equipment design and its benefits and costs to the nation.
- A description of a proposed laboratory facility to test the operation of a prototype HELPS device on a full-scale, oil-fired, residential furnace.

These discussions are organized as separate sections of the present report. The study concludes with a summation of the most important findings as well as recommendations for further work.

SECTION 3

HEATING FOR THE RESIDENTIAL SECTOR

This section of the present report begins the task of assessing the feasibility of a direct contact heat and emission loss prevention system (HELPS) by discussing the design, operating and emission characteristics of residential heating equipment and by noting which of these factors may be critical for HELPS concepts. Topics covered include:

- Residential heating equipment
- Energy consumption and emissions

The section ends with a summary and the major conclusions.

3.1 RESIDENTIAL HEATING EQUIPMENT

Figure 3-1 gives a breakdown of the major types of residential heating equipment. The prevalent designs are the warm air furnace and hydronic systems, as shown in Table 3-1. Regional distributions of residential heating equipment by type and by fuel are given in Tables 3-2 and 3-3. Fuel usage is given in Table 3-4. The data show that hydronic equipment and distillate oil are the dominant equipment type and fuel in the Northeast, while warm air furnaces and natural gas are most popular in the rest of the country. In any case, according to data obtained from the Gas Appliance Manufacturers Association (GAMA), the trend in the last 10 years has been forced warm air systems.

Equipment characterization and HELPS concept evaluation will, therefore, concentrate on application to warm air furnaces and steam or hot water units, the latter overlapping to some extent on the commercial heating sector (that is, cast iron boilers are used for both residential and commercial heating applications).

Warm Air Furances

A warm air furnace is a self-enclosed appliance used for heating air for a house or building. It discharges hot air directly into the space being heated or more commonly through ducts which transport the warm air to the area to be heated. Some furnaces operate by gravity (buoyancy forces),

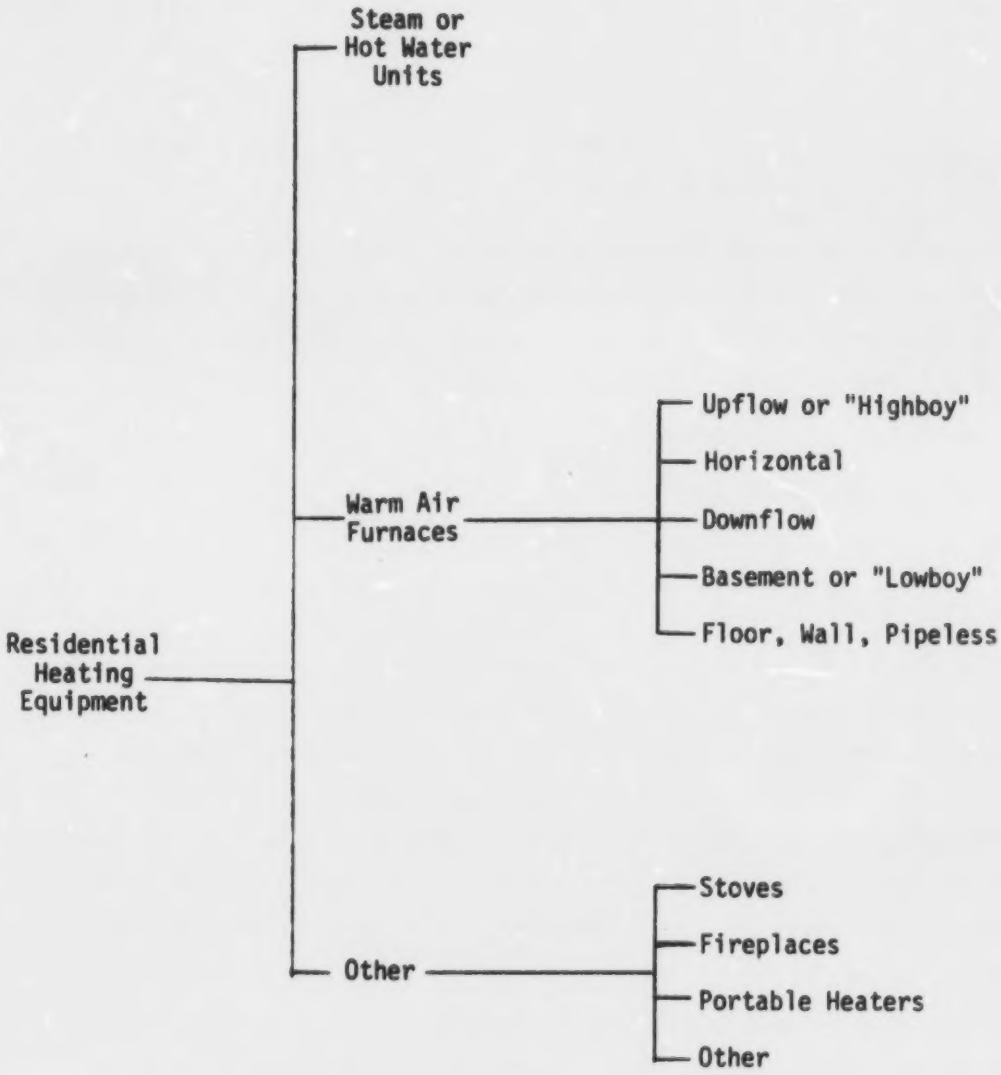


Figure 3-1. Residential heating equipment types.

TABLE 3-1. DISTRIBUTION OF RESIDENTIAL HEATING SYSTEMS FROM THE 1970 U.S. CENSUS

Equipment Type	Total	Percent	Rank
Steam or Hot Water			
Gas	5,110,201	8.78	5
Fuel Oil	7,151,549	12.29	2
Coal or Coke	591,114	1.02	
Wood	Nil		
Electricity	Nil		
Bottled, Tank, or LP Gas	160,092	0.28	
Other Fuel	207,366	0.36	
Warm Air Furnace			
Gas	18,357,930	31.56	1
Fuel Oil	6,031,061	10.37	4
Coal or Coke	583,648	1.00	
Wood	Nil		
Electricity	Nil		
Bottled, Tank, or LP Gas	1,191,579	2.04	9
Other Fuel	44,848	0.08	
Floor, Wall, or Pipeless			
Gas	4,530,875	7.79	6
Fuel Oil	571,646	0.98	
Coal	61,281	0.10	
Wood	Nil		
Electricity	Nil		
Bottled, Tank, or LP Gas	377,622	0.65	
Other Fuel	7,120	0.01	
Other Heating Equipment			
Gas	7,014,739	12.06	3
Fuel Oil	2,719,214	4.67	7
Coal	584,909	1.00	
Wood	793,908	1.36	10
Electricity	Nil		
Bottled, Tank, or LP Gas	2,076,655	3.57	8
Other Fuel	6,932	0.01	
TOTAL	58,174,289	99.98	

TABLE 3-2. REGIONAL DISTRIBUTION OF RESIDENTIAL HEATING EQUIPMENT TYPES FROM THE 1970 U.S. CENSUS (PERCENT)

Heating Equipment Type	Region			
	Northeast	Northcentral	Southwest	West
Steam or hot water	56.2	16.0	5.9	5.1
Warm air furnace	31.6	64.5	34.9	41.1
Built-in electric units	2.6	2.3	7.4	8.8
Floor, wall, or pipelines	1.8	4.3	10.8	22.1
Room heaters with flue	5.3	10.2	15.7	14.2
Room heaters without flue	1.1	1.3	14.8	2.8
Fireplaces, stoves, portable heaters	1.3	1.4	0.6	2.2
None	0.1	0.0	0.6	2.2

TABLE 3-3. REGIONAL DISTRIBUTION OF FUEL USE FROM THE 1970 U.S. CENSUS (PERCENT)

Fuel	Region			
	Northeast	Northcentral	Southwest	West
Utility gas	37.1	66.8	50.0	71.1
Distillate oil	54.4	19.6	18.9	8.8
Coal or coke	3.5	3.3	3.2	0.7
Wood	0.2	0.4	2.9	1.3
Electricity	3.1	3.1	13.2	11.7
Bottled, tank, or LP gas	1.1	6.3	10.9	5.8
Other	0.7	0.5	0.2	0.4
None	0.1	0.1	0.6	2.2

TABLE 3-4. FUEL USAGE BY EQUIPMENT CATEGORY (Reference 34)

Heating Equipment Type	Fuel Type	Fuel Usage (10^{12} Btu/yr)
Warm air furnaces	Oil	1873.0
	Gas	2858.0
Hydronic	Oil	1698.0
	Gas	975.6
Floor, wall pipeless	Oil	280.0
	Gas	658.5
Room heater with flue	Oil	420.0
	Gas	682.9
Room heater without flue	Oil	268.3

but the majority are forced air systems, using a pressure blower to move the air through the ducts and back to the furnace (References 1, 2, and 3).

The furnace consists of a burner with related piping and controls, a heat exchanger, and a blower for forced air systems. The furnace package is enclosed in a rectangular steel casing. The heat exchanger compartment is insulated to improve efficiency and to limit the outer casing temperature for personnel safety. The combustion takes place in the primary combustion space of the metal-walled heat exchanger. The combustion products pass through secondary flue gas passageways of the heat exchanger and exit through a flue to the atmosphere. The air to be heated circulates over the outside of the heat exchanger to the warm air discharge. The air discharged is heated in the range of 100°F to 150°F. Furnaces are fired by natural gas and distillate oil and (rarely) by coal.

Domestic or residential warm air furnaces are available in capacities under 300 x 10^3 Btu/hr and are generally classified into four types:

- Downflow, in which the blower is mounted above the heat exchanger, the flue gas discharges at the side or top and the warm air discharges from the bottom of the unit (counter-flow). Figure 3-2 shows a typical gas-fired downflow unit, while Figures 3-3 and 3-4 show counterpart oil-fired furnaces utilizing two different heat exchanger designs.
- Upflow or "high-boy", which is similar to downflow except that the blower is mounted below the heat exchanger and both the warm air and flue gas discharge from the top of the unit (co-flow). Gas-fired furnaces of this type mounted with direct and belt-driven blowers are shown in Figure 3-5. Figure 3-6 illustrates the same furnace design fired by oil.
- Horizontal, in which the blower is mounted next to the heat exchanger, the flue gas discharging at the top and the warm air at the end of the unit (Figures 3-7 and 3-8).
- Basement of "low-boy", which is very similar to the horizontal unit except that the flue gas discharges at the side and the warm air from the top. In addition, the heat exchanger may be higher and narrower than for a horizontal furnace.

All of these units are available in a wide range of capacities. The choice of the appropriate type is based most often on available installation space. For example, horizontal units are intended for use in situations where headroom is limited, such as in attics or crawl spaces.

Sub-types of warm air furnaces include space heaters and unit heaters. A warm air furnace is known as a space heater or unit heater when it discharges directly into the space being heated

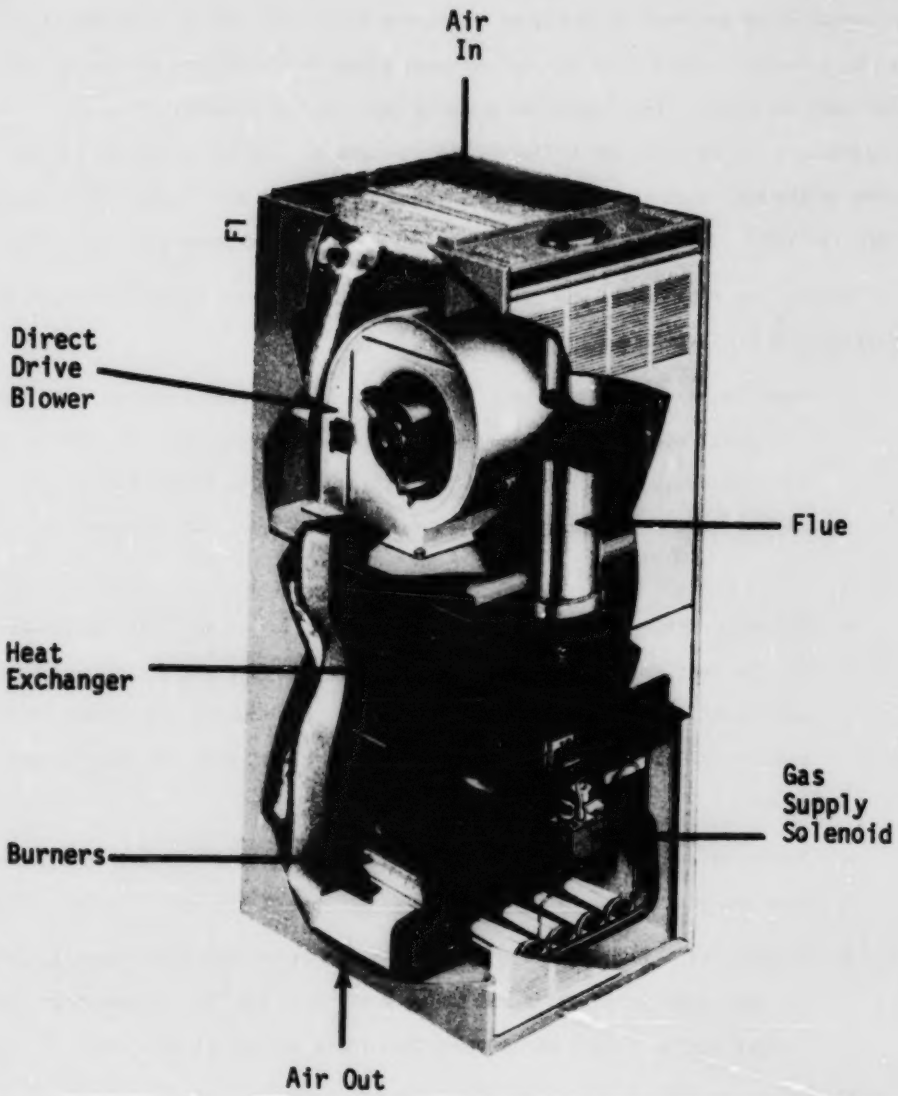


Figure 3-2. Forced warm air gas-fired furnace — downflow (note: Figures 3-2 through 3-8 courtesy of the Lennox Co.).

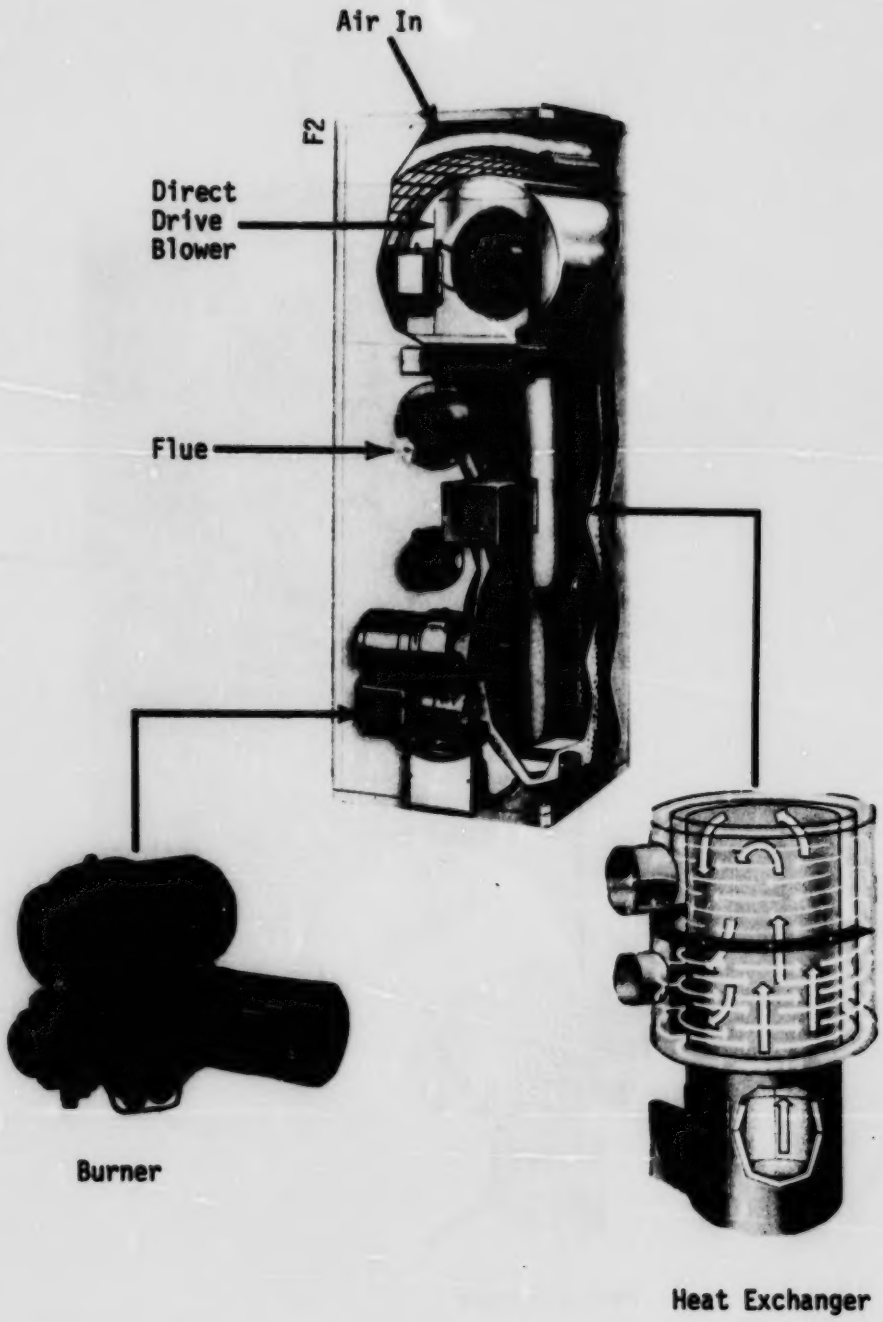


Figure 3-3. Forced warm air oil-fired furnace – downflow.

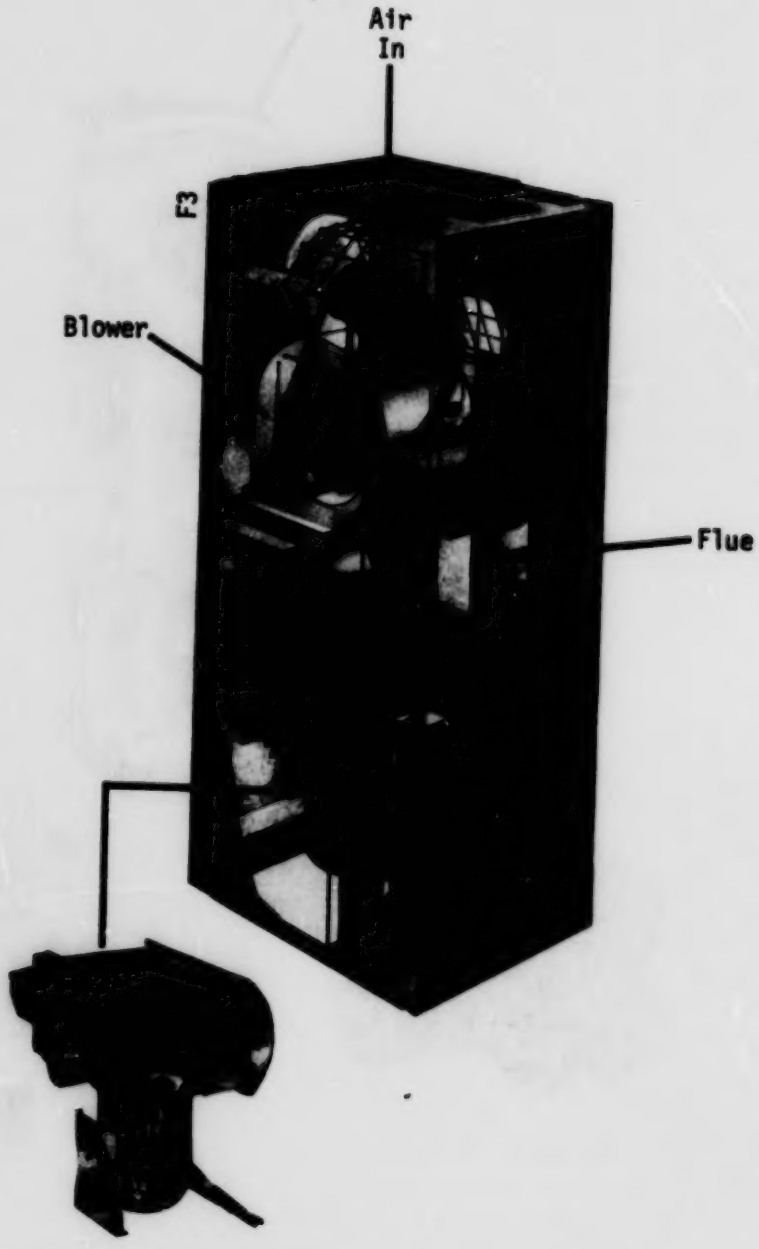
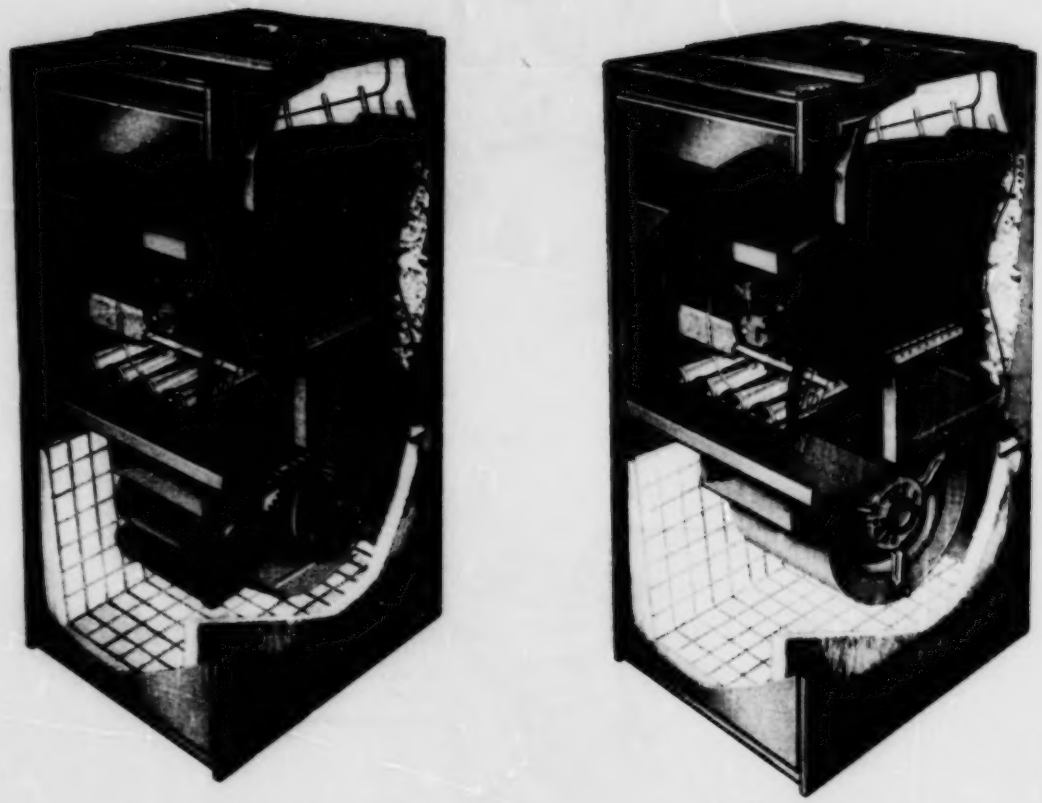


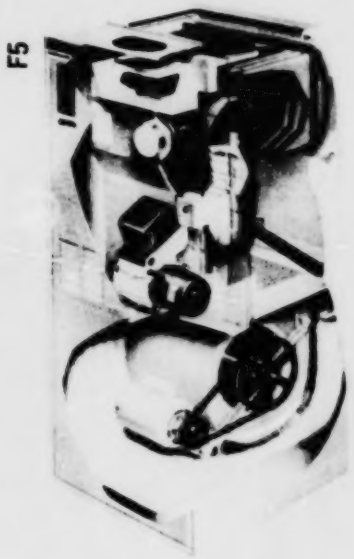
Figure 3-4. Forced warm air oil-fired — downflow, with compact heat exchanger.



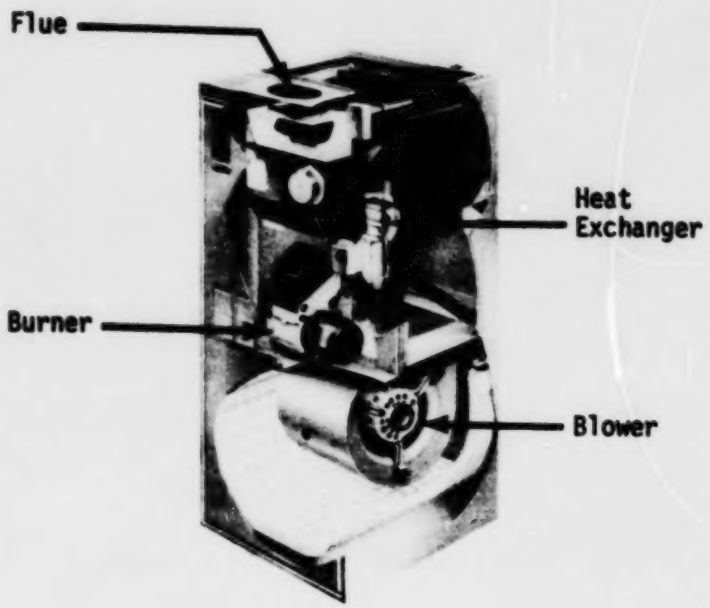
Belt drive blower

Direct drive blower

Figure 3-5. Forced warm air gas-fired furnace – upflow.



Belt drive blower



Direct drive blower

Figure 3-6. Forced warm air oil-fired furnace — upflow.

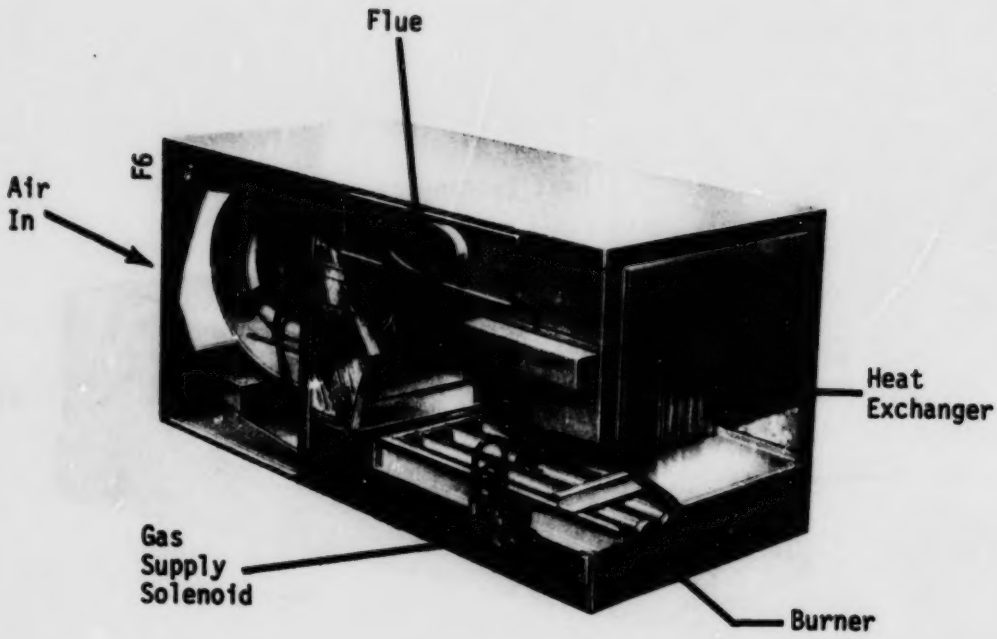


Figure 3-7. Forced warm air gas-fired furnace – horizontal.

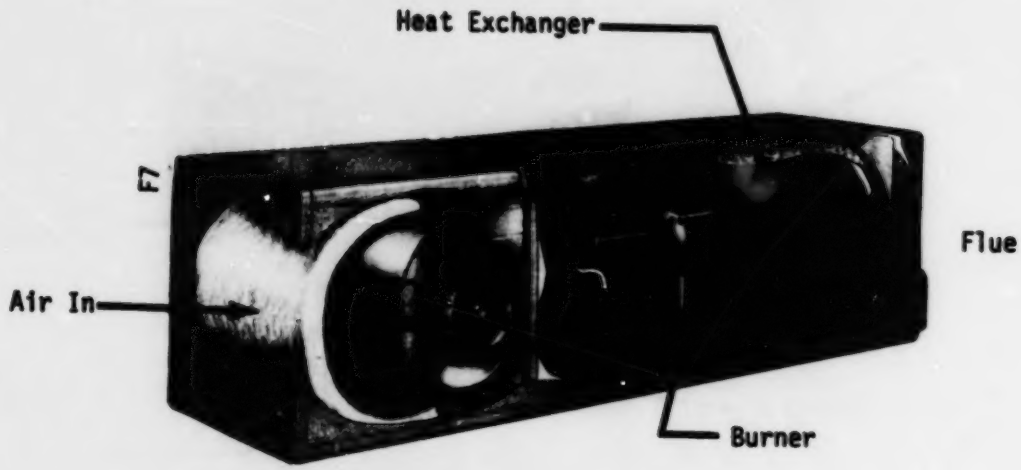


Figure 3-8. Forced warm air oil-fired furnace — horizontal.

and has no ducts. By definition of the American Gas Association, a unit heater is non-residential (larger than domestic). While domestic heaters may be used in commercial installation, commercial or industrial size heaters are seldom used in domestic applications.

Space heaters are designed as room heaters, wall furnaces and floor furnaces. A room heater is a self-contained, free standing, gas-fired air heater installed in the space being heated. It may employ gravity or forced air circulation and be vented or unvented. Wall furnaces are similar but are designed to be mounted in a wall and are vented. A floor furnace is mounted under a floor with a grill at floor level. Unit heaters may be free-standing floor units or may be designed for suspension from the ceiling.

The heat exchanger in a warm air furnace can have a single combustion chamber, usually cylindrical, or a series of individual sections. The single combustion chamber is used with a single port oil-fired burner, as shown in Figure 3-3. It is usually lined with insulating refractory or felt insulation but can be fabricated from a temperature resistant alloy steel. The sectional type is used with multiple gas-fired burners which are cross-connected to use a single port. This type is illustrated in Figure 3-4. The exchanger sections are connected at the bottom and at the top to a common flue gas breeching. Construction may be of alloy steel, stainless steel or sometimes aluminized steel.

Two types of blowers are found on modern forced warm air furnaces: Direct drive and belt drive. Direct drive blowers are of the multiple speed type and usually are found on combination heating and cooling furnaces. However, they are also used on heating furnaces only. When properly connected electrically, the blower will run at slower speeds in the winter months and at a faster speed during the summer months.

Belt drive blowers operate at one speed, which is dependent on the adjustment of the pulley system. This speed is set by the servicemen during furnace installation, and can have a major impact on efficiency if done improperly.

The gas burners on residential-size warm air furnaces are naturally aspirated types consisting of three to four venturis, with distribution pipes consisting of rows of small orifices (Figure 3-2). The primary air is drawn into the venturi by the gas pressure and premixes with the gas prior to ignition. The primary air/fuel ratio can be controlled by small shutters at the end of each venturi. Secondary air from the furnace room enters around the burners to quench the peak flame temperature and allow complete combustion. Units always utilize draft diverters which dilute the flue gas stream and prevent downdrafts from blowing out the pilot.

Typical operating conditions of a domestic-size gas-fired, warm air furnace (100,000 Btu/hr) are given in Table 3-5. The wide range in excess air levels is due to variations in installations and metrological conditions. The combustion chamber pressures are quite low due to the naturally aspirated burners. Consequently, the heat transfer open area on the flue gas side is quite large to prevent excessive pressure drop. This results in the fairly low heat transfer coefficients on the hot side, as shown in Table 3-5, which necessitates fairly large surface areas. An overall heat transfer coefficient of 2.7 Btu/hr-ft^2-°F is recommended by the American Society of Heating Refrigerating and Ventilation Engineers (ASHRAE).

Gas-fired furnaces rely on the stack to create sufficient draft to draw the secondary air through the furnace. Manufacturers frequently claim that reducing the stack temperature below 300°F will result in insufficient draft for the burners and cause condensation in the stack.

In all, the design procedure of gas-fired forced warm air furnaces is largely empirical and relies on testing and modifications of experimental units to meet AGA/ANSI standards.

Oil-fired forced warm air furnaces look very similar to the gas-fired units from the outside and are now being made with overall volumes not much greater than the gas-fired versions. There are considerable differences internally, however. The heat is supplied by a gun type oil burner of the type pictured in Figure 3-3. These burners consist of a combustion air blower, motor, damper, and oil pump. Fuel flow rate is determined by the oil nozzle orifice size, and the total air flow rate by the blower and damper. The proper air/fuel ratio is adjusted using the damper until the optimum CO and smoke levels are achieved.

The burner is mounted in a refractory or refractory-felt lined combustion chamber which is cooled by air circulating through the house. From the combustion chamber the flue gas passes through a heat exchanger, as discussed previously, and finally out the stack. The absence of a pilot flame and the use of a forced draft system precludes the need for a draft diverter in the flue. The burner blower may supply the full pressure to exhaust the gas from the stack or it may rely partially on the buoyancy forces downstream of the stack. Table 3-6 lists typical operating conditions for this type of furnace.

As for gas-fired furnaces, the design procedure is quite empirical and relies on prototype development, experience, and testing. Standards for construction and thermal efficiency are set by Underwriters Laboratory and ANSI.

One of the most important attributes of a conventional warm air furnace is the cyclical operating mode. This often contributes to an overall thermal efficiency of significantly less than the

TABLE 3-5. CHARACTERISTICS OF A TYPICAL 10^5 BTU/HR FORCED WARM AIR GAS-FIRED FURNACE*

Excess Air: 20% to 300%
Flue Exit Diameter: 3-1/2" to 5"
Heat Exchanger Area: ~30 to 35 ft^2
Overall Heat Transfer Coefficient: 2 to 3 Btu/hr-ft^2-°F
Exit Flue Gas Temperature (Before Draft Diverter): 450°F to 650°F
Draft Diverter Dilution Air Flow Percent of Flue: 20% to 50%
Combustion Chamber Pressure: ±0.2" W.G.
Recirculating Air Flowrate (scfm): 800 to 1200 scfm
Temperature Rise on Air Side: 70°F to 75°F
Maximum Gas Side Heat Exchanger Temperature: 900°F
Overall Steady State Efficiency: 75% to 80%
Common Operating Mode: on/off
Ignition System: Pilot flame
Draft System: Natural

*Data is compiled from discussions with manufacturers and from References 3 through 7.

TABLE 3-6. CHARACTERISTICS OF A TYPICAL 10^5 BTU/HR WARM AIR, OIL-FIRED FURNACE

Excess Air: 30% to 100%
Flue Exit Diameter: 5" to 7" (round)
Heat Exchange Area: 20 ft^2 to 30 ft^2
Overall Heat Transfer Coefficient: 2 to 3 Btu/hr-ft^2-°F
Exit Flue Gas Temperature: 400°F to 600°F
Combustion Chamber Pressure: 0.05" W.G. to 0.2" W.G.
Recirculating Air Flow: 800 to 1300 scfm
Temperature Rise on Air Side: 75°F to 80°F
Maximum Gas Side Heat Exchanger Temperature: 900°F
Overall Steady State Efficiency: 70% to 75%
Common Operating Mode: on/off
Ignition System: Spark
Draft System: Forced

standard 80 percent. A 1970 study by Stricker (Reference 8) attempted to measure the efficiencies of gas- and oil-fired warm air furnaces in the "as-found" condition in the field over a 6-month period. Figures 3-9 and 3-10 from this study show the typical temperature rise on the air side during a cycle. The fire is extinguished at the peak temperature rise, and it is at this point that the peak, or certified, efficiency is probably achieved. For the remainder of the cycle the air blower remains on but the flue gas temperatures and flowrates have dropped. Perhaps what is more important and not shown on this curve is that the burner has been firing for several seconds prior to blower start-up. Again, this means that there is a significant period of time when there is very little flow on the air side, implying inefficient heat exchange. Of course, some of this heat is stored as heat capacitance in the furnace structure to be recovered eventually, but much of it escapes out the stack under inefficient conditions.

One type of warm air furnace that bears further discussion is the roof-mounted commercial-size unit. The designs of these units vary considerably among manufacturers, differing from the residential sector. The apparent standardization of the latter is due mainly to the large sales volume as well as an extremely competitive market place. These conditions differ sufficiently in the commercial heating sector to allow some design innovations, especially in gas-fired units.

The burners in these units tend to be inherently more versatile. One such unit, used in rooftop furnaces manufactured by the Trane Company, consists of a "Series NP Maxon Burner" with a 25 to 1 turndown capability.

Novel heat exchangers are also more common in these units, such as the "Multiloy" type found on General Electric products. This heat exchanger is composed of a bundle of parallel stainless steel fire tubes with numerous small cooling fins welded to the outside.

Higher quality materials of construction and larger interior volumes are other factors that distinguish commercial-size from domestic-size furnaces.

Cast Iron Boilers – Capacities up to 13.5 x 10^6 Btu/hr (References 1 and 2)

The domestic and small commercial boilers sold today have heat exchangers that are constructed of cast iron. They are designed for supplying low pressure steam (15 psig maximum) or hot water (40 psig maximum) and are used primarily for air or water heating systems.

These boilers usually consist of an assembly of vertical cast iron sections. Water enters at the bottom of the sections and hot water or steam exits at the top. The products of combustion are conducted through ladyrinth passages cast into the sections. The capacity of a sectional boiler may be varied by the addition or deletion of sections.

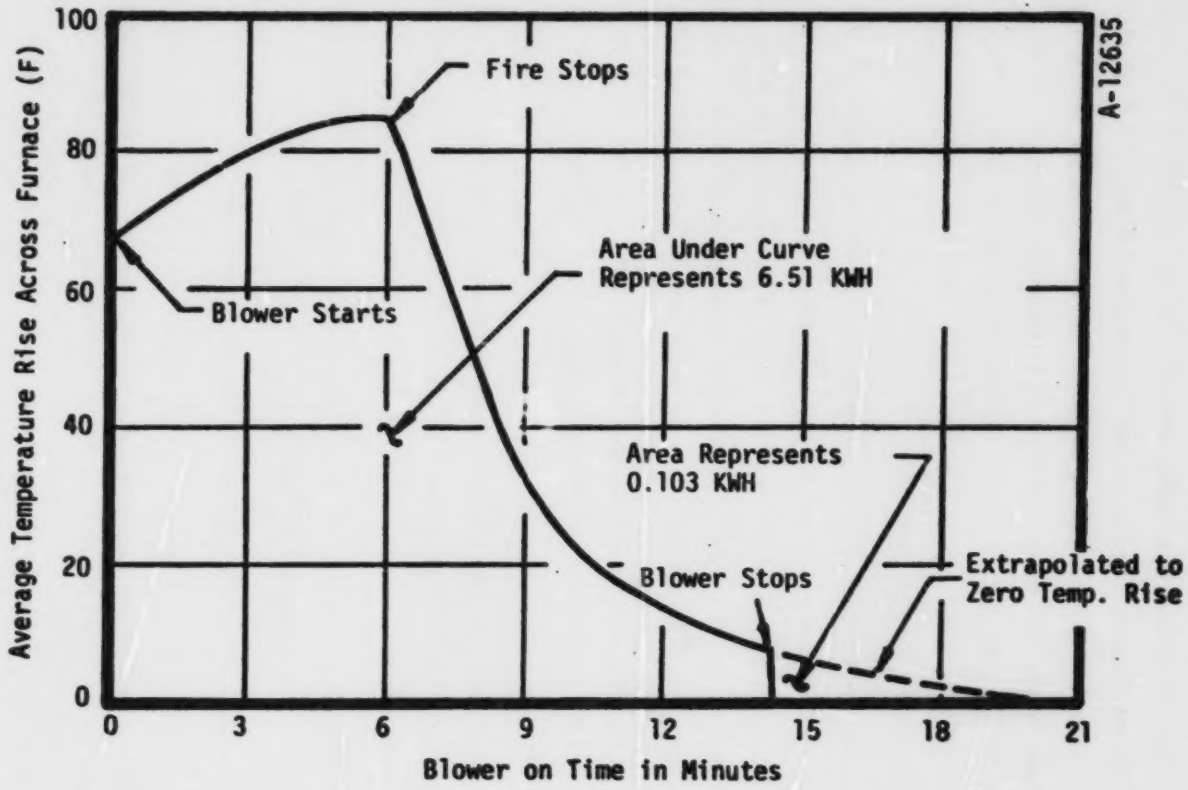


Figure 3-9. Temperature rise across a gas-fired warm air furnace during a typical cycle.

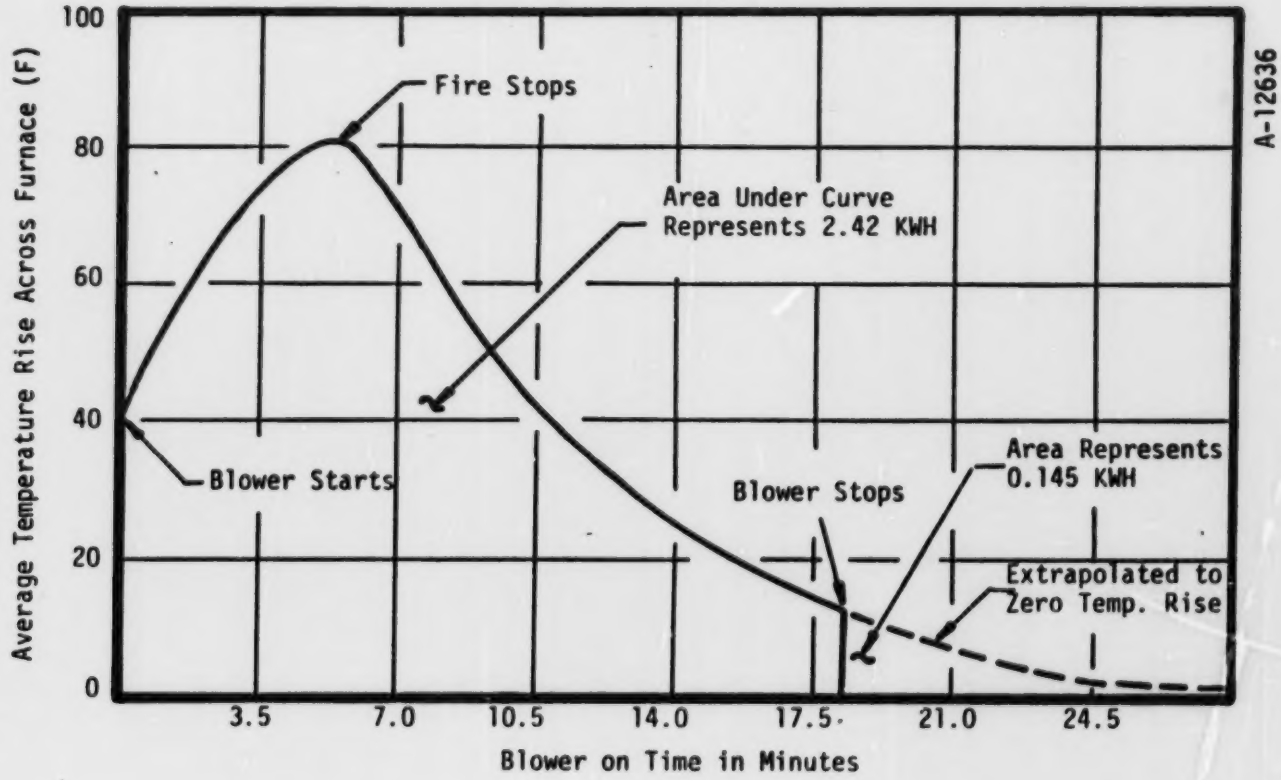


Figure 3-10. Temperature rise across an oil-fired warm air furnace during a typical cycle.

Cast iron boilers tend to be more expensive than steel firetube boilers, but they are more reliable, longer lived, and require less maintenance. One disadvantage of cast iron boilers is that the sections tend to deform and take a permanent set due to thermal expansion which can lead to flue gas leaks at the joints and around the doors.

Figure 3-11 shows a typical gas-fired cast iron boiler. New units are usually considerably more expensive than forced air systems and are, therefore, now being made only in the larger size ranges of 130,000 Btu/hr and higher. However, old units are still prevalent in the Northeastern and Northcentral regions of the country. The natural gas supply systems on the newly-designed units are quite similar to the warm air furnace, utilizing naturally aspirated burners.

Heat transfer area is governed by the gas side transfer coefficient which is once again limited by the pressure drop requirements of the burners.

Figure 3-12 shows an oil-fired cast iron boiler. Again, although quite common in older homes in the Northeast states, these units are now quite costly and are limited to the larger size ranges. These boilers are similar in some respects to oil-fired warm air furnaces in that they employ a refractory-lined combustion chamber followed by the heat exchange surface. Nor draft diverter is required, and flue gas temperatures match those found in warm air furnaces.

It has been reported that poor matching of burner and combustion chamber requirements frequently occurs between the burner manufacturer and furnace manufacturer (Reference 9). Typically, considerable leakage of secondary air into the firebox is allowed, which serves to lower the flame temperature. In many cases this is necessary to prevent damage to the combustion chamber, but leakage probably results in overall lower furnace efficiency. Typical operating conditions and design factors for both oil- and gas-fired systems are given in Table 3-7.

Cast iron boilers are rated by the Hydronics Institute (IBR ratings). They must be designed and constructed in accordance with the ASME Code, Section IV, Heating Boilers. The IBR Testing and Rating Code specifies the test conditions and such things as minimum efficiency, percentage of carbon dioxide in the flue gas, flue gas temperature and smoke reading. The ratings cover a range of 48×10^3 Btu/hr to 13.5×10^6 Btu/hr.

3.2 ENERGY CONSUMPTION AND EMISSIONS

According to a recent study of energy consumption patterns in the U.S. (Reference 10), the residential sector accounted for 19 percent of the total energy consumption of the United States in 1968. Almost 60 percent of this figure, or 11 percent of the nation's total, was used for space

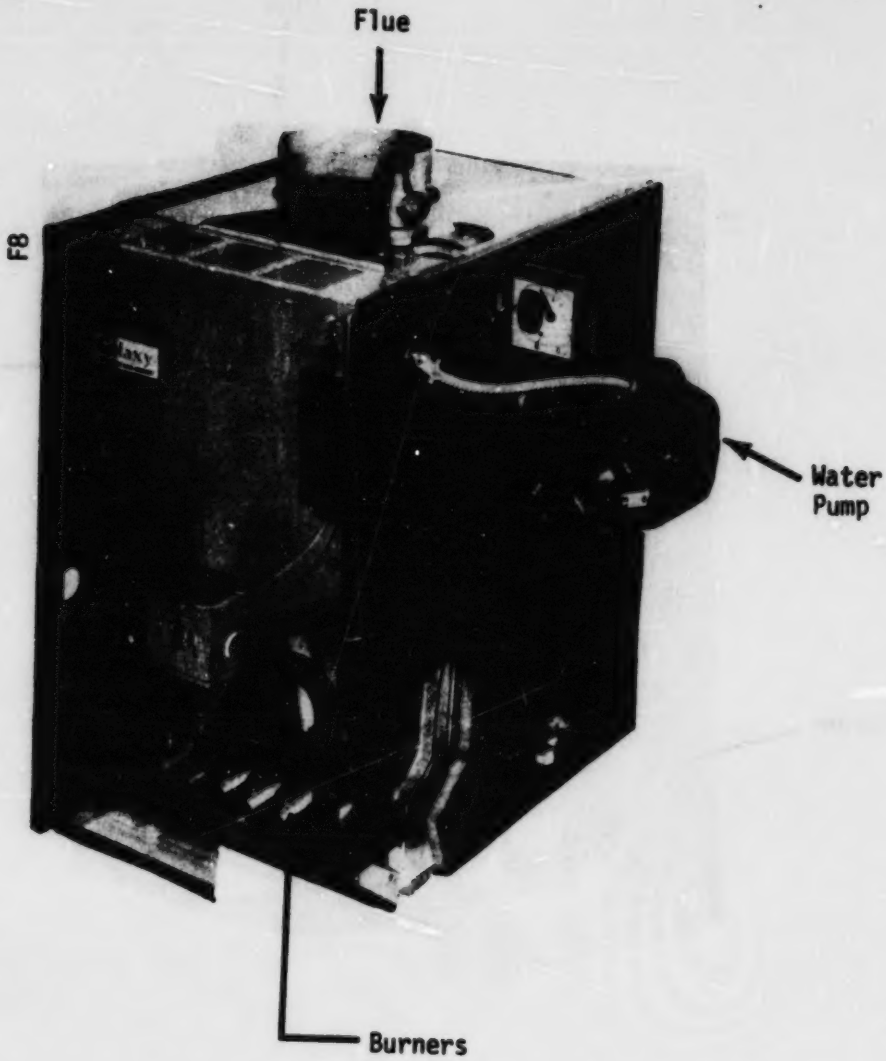


Figure 3-11. Gas-fired cast iron boiler (courtesy of Slant-Fin Corporation).

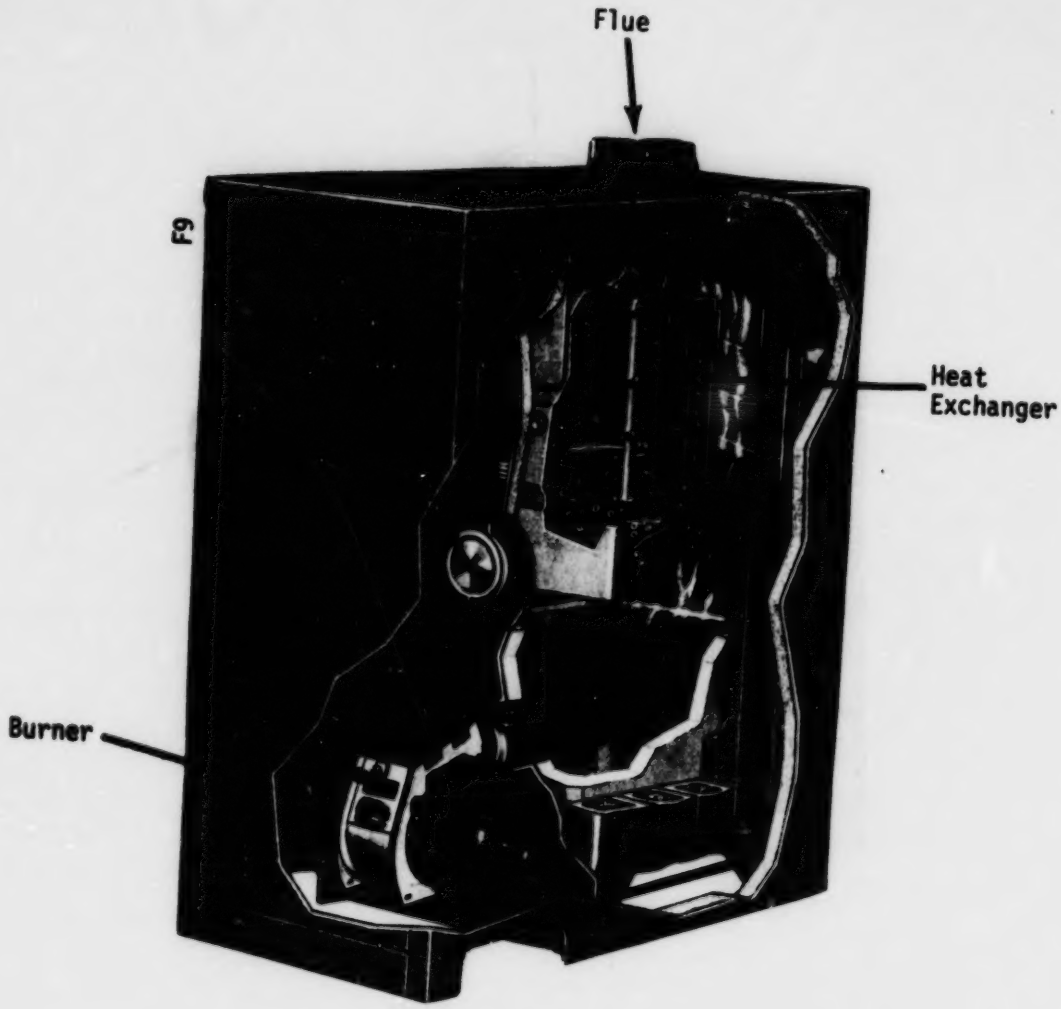


Figure 3-12. Oil-fired cast iron boiler (courtesy of the Utica Radiation Company).

TABLE 3-7. CHARACTERISTICS OF TYPICAL 10^5 BTU/HR GAS- AND OIL-FIRED CAST IRON BOILERS

	Gas	Oil
Recirculating water flows (gpm)	3 to 15	3 to 15
Excess air (percent)	30 to 500	30 to 100
Flue exit diameter (inches)	3 to 5	3 to 5
Exit flue gas temp, upstream draft diverter (°F)	500 to 600	400 to 600
Exit flue gas temp, downstream draft diverter (°F)	300 to 400	300 to 400
Combustion chamber pressure ("W.G.)	0.05 to 2	0 to 2
Temperature rise on water side (°F)	10 to 40	10 to 40
Overall steady state efficiency (percent)	75 to 80	70 to 75

heating. Oil-fired equipment, the focus of the HELPS program, accounted for 18 percent of residential energy consumption, or 6 percent of the nation's total. At an annual growth rate of 1 percent, the reduction of energy use by oil-fired space heating equipment is definitely a valid goal and one that will be pursued by the HELPS program.

Unlike fuel usage and energy consumption, the types and quantities of pollutant emissions from such diffuse area sources as residential heating equipment are more difficult to characterize. One investigator (Reference 11) estimated that air pollution from the combination of residential and commercial heating sources constitutes about 10 percent of the national total (summation of mass of particulate, SO_x, NO_x, CO, and unburned hydrocarbons). This figure, however, may be outdated; the source paper was published in 1964. Fuel usage and emission factors were the basis for this estimate.

Another data source, EPA's National Emission Data System (NEDS), does not compile information for sources that emit less than 25 tons/year of any pollutant. This limitation causes the exclusion of residential heating from consideration. From all indications, however, this contribution to the nation's total emissions probably falls in the 1 to 10 percent range.

The emissions from commercial and residential space heating for one pollutant species, oxides of nitrogen, have been fairly well established by recent studies. The 1972 data from reference 12 gives an estimate of 826,800 tons/year (7.1 percent of total) as the contribution from commercial and residential heating. Specific emission quantities from oil-fired residential heating systems are difficult to establish.

In any case, their impact on air quality was deemed sufficiently significant that the U.S. Environmental Protection Agency has investigated an emission reduction R&D program.

To aid in this effort, the EPA is conducting research on the reduction of air pollution from various types of residential heaters. Early work was performed on an experimental furnace to determine the basic reduction parameters. Later, commercially available equipment was investigated. The most recent published work from this project appeared in References 13 and 14.

This latter study, which concentrated on an oil-fired warm air furnace, showed that residence time, flame retention devices, maintenance, and excess air are major factors in the control of emissions, the latter being the dominant one. Emissions of CO, UHC, smoke, and particulates pass through a minimum as excess air is increased from stoichiometric, as shown in Figure 3-13. It is observed that both thermal efficiency and NO_x emissions behave in the opposite manner: as excess air is increased, they pass through maximum points.

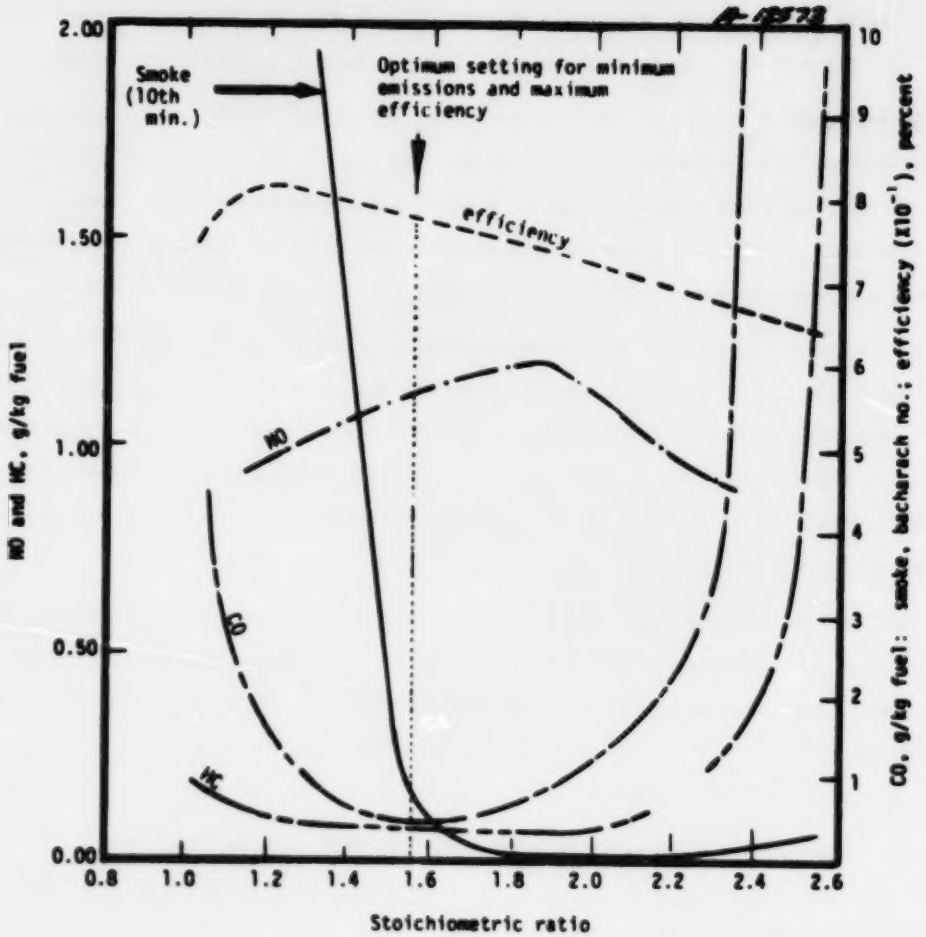


Figure 3-13. General trend of smoke, gaseous emissions, and efficiency versus stoichiometric ratio.

At stoichiometric ratios ranging from 1.2 to 1.5, the NO_x, HC, and CO emissions from various types of gas-fired burners averaged 0.104, 0.0032, and 0.051 g/10^6 cal input, respectively. Emissions of the same species from equivalent size oil burners were comparable to these levels, with particulates being a problem only from this fuel. Compared to other sources of air pollution, the levels of UHC and CO from properly adjusted furnaces are very low.

Combustion chamber material was found to affect all emissions. Furnaces with steel-lined chambers required higher excess air levels to reach optimum emission levels, thus reducing efficiency. The shape of the combustion chamber had little effect on pollutant generation.

As mentioned in Section 3.1 of this report, the on/off mode is the outstanding operating characteristic of warm air furnaces, and is the major efficiency reducing factor. The aforementioned EPA study has since identified the importance of cyclic-based emissions. Work on a model residential heating system indicated that the sizeable peak emissions measured during ignition and shutdown can account for most of the total emissions.

CO and UHC emissions peak at ignition and shutoff as shown qualitatively in Figure 3-14. HC concentration drops to insignificant levels between the peaks, while CO emissions tend to flatten out at a measurable level. Figure 3-15 shows that particulate matter continuously tapers off after the ignition-induced peak. Figure 3-16 shows that, after an initial peak, the NO emission level continues to rise. The operating time of most domestic burners seemingly is not long enough for NO to reach equilibrium levels.

The transient emissions are caused mainly by variations in the combustion chamber temperature. At ignition, a cold refractory will not support complete combustion, producing peaks of CO, UHC, and smoke. These peaks could be eliminated by keeping the refractory warm during the off-time by a pilot or modulating burner. NO_x emissions show a continuous increase due to the steadily rising temperature of the combustion chamber walls.

It is important to recognize that cyclic-based emissions mainly affect emissions of CO and UHC, both of which are very low for oil burners in any case. It is hoped that particulate emissions can be reduced by new burner designs.

In all, it appears that the literature does not contain definitive, unambiguous source testing data of the sort that would be required for input to the present HELPS feasibility study. For this reason, EPA emission factors, given in Table 3-8, will be used for the analysis of the emission reduction potential performed in Section 5 of this report. The HELPS device will be applicable

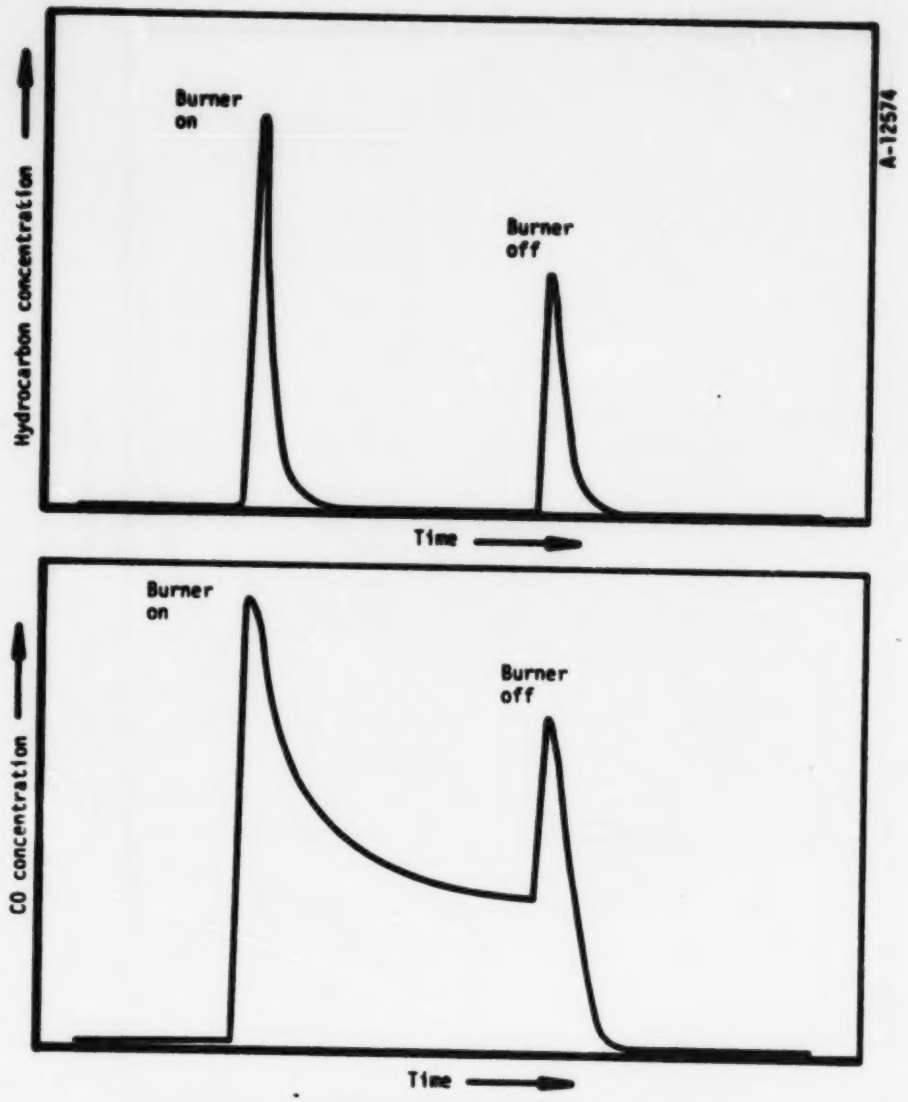


Figure 3-14. Hydrocarbon and carbon monoxide trends during cycle.

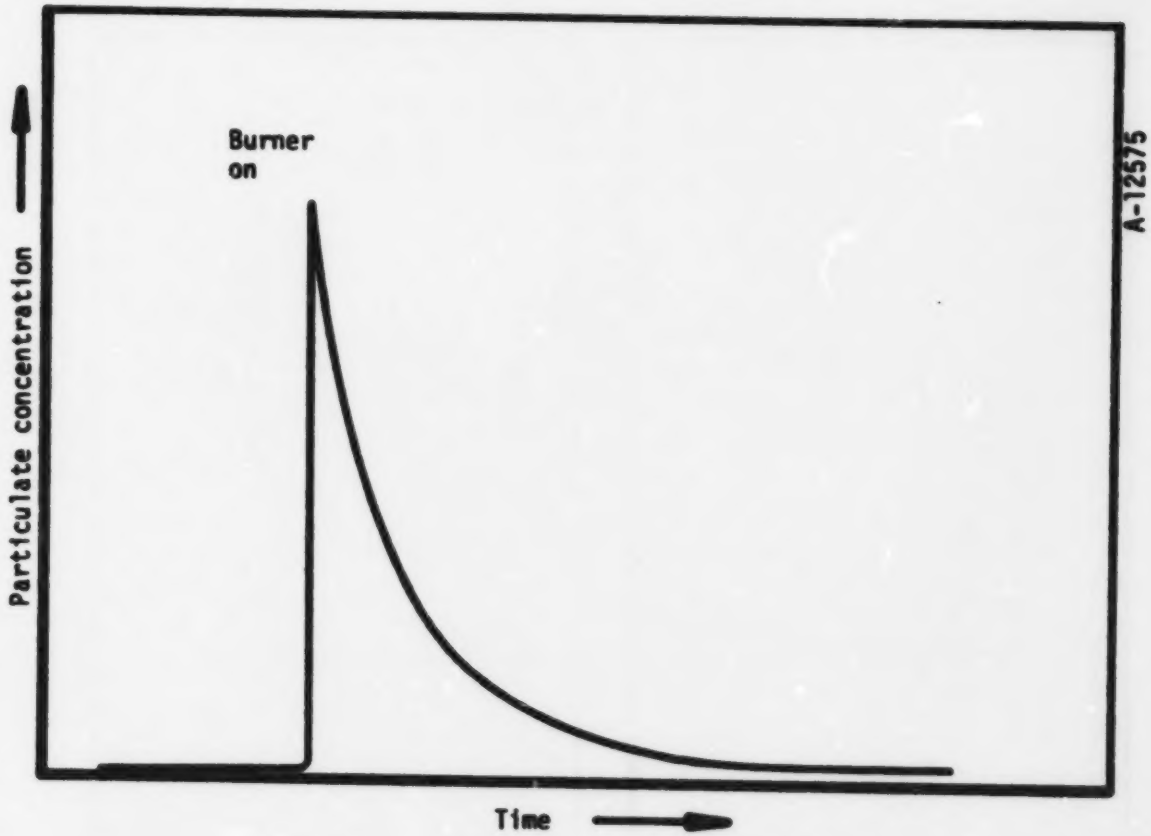


Figure 3-15. Particulate trends during cycle.

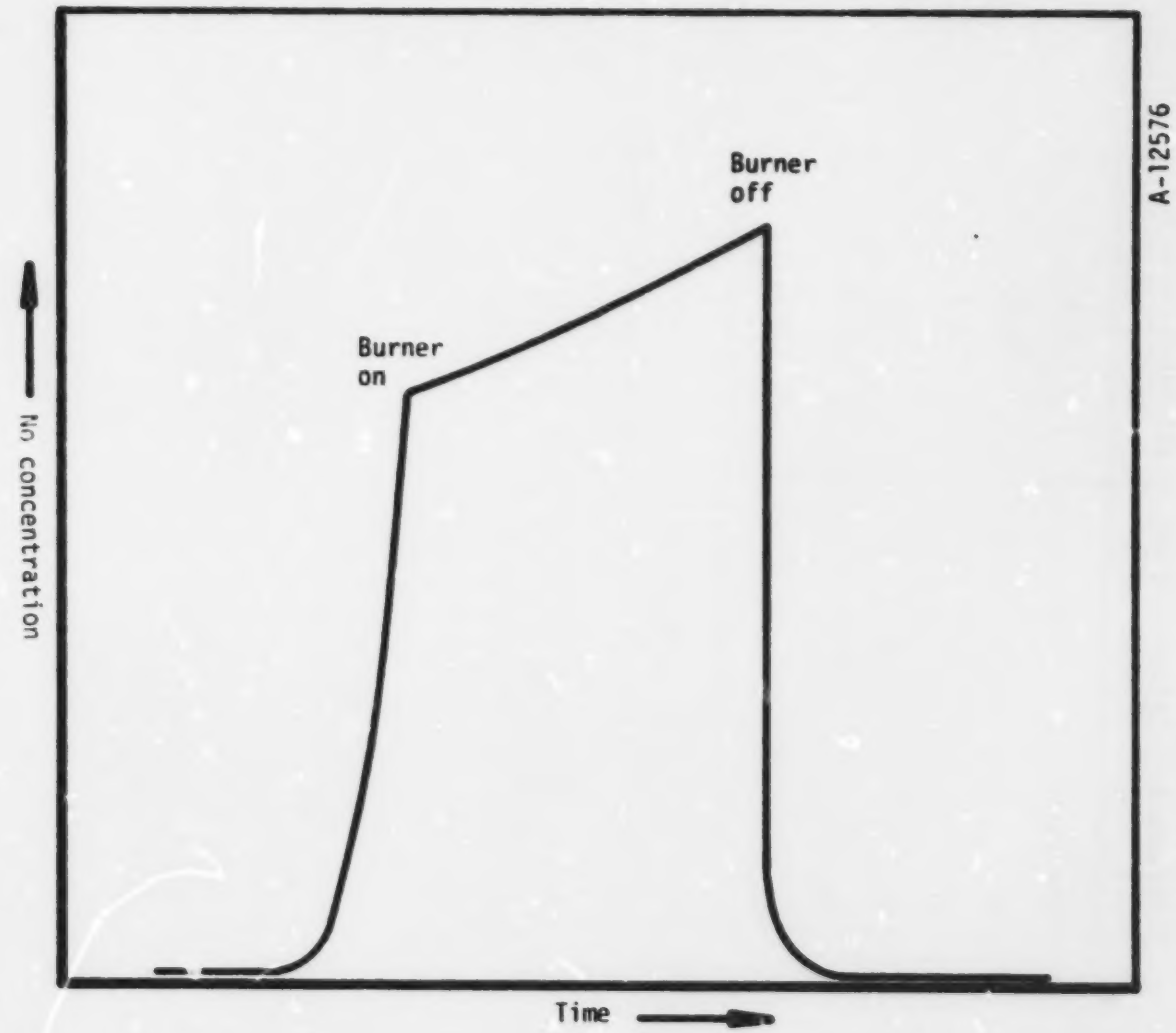


Figure 3-16. Nitric oxide trend during cycle.

TABLE 3-8. EMISSION FACTORS FOR OIL-FIRED RESIDENTIAL HEATING UNITS (Reference 15)

Pollutant	Emission Factor ($lb/10^3$ gal)	Estimated Emissions (10^7 lb/yr)
Particulate	2.5	6.5
CO	5	12.9
HC	1	2.6
NO_x	18	46.6
SO_2	142S*	367.5S
SO_3	2S*	5.2S

*S = percent of sulfur in oil.

mainly to oil-fired warm air furnaces and hydronic systems. According to Table 3-4, the annual fuel usage for these equipment types amounts to 3571 x 10^{12} Btu/yr. Assuming a fuel oil heating value of 138,000 Btu/gal, the emission quantities shown in Table 3-8 were calculated.

3.3 SUMMARY

The preceding discussion centered on the characterization of space heating for the residential sector. This sector is defined by equipment types, energy consumption, and air pollutant emissions.

The most popular type of heating equipment is the warm air furnace, followed by hydronic systems which are representative of older heating methods. The oil-fired versions of these equipment types, the foci of the HELPS study, comprise 22 percent of the nation's total number of residential heating units, and account for about 6 percent of the nation's total energy consumption. Their contribution to the nation's total air pollutant loading is undefined, but probably falls between 1 and 10 percent. The updated EPA emission factors will be used as the baseline for describing air uncontrolled oil-fired residential heater.

It is recommended that a typical residential, oil-fired warm air furnace of intermediate heat release be considered in a laboratory analysis of the feasibility of the HELPS concepts. Such a unit has already been purchased by the EPA for this purpose, and is currently stored in the Aerotherm Combustion Research Laboratory.

SECTION 4

EMISSION REDUCTION AND ENERGY CONSERVATION METHODS

This section of the present report reviews the major options available for reducing both the emissions from and the energy consumption of residential heating systems. The former goal can be accomplished by modification of the combustion process as well as by the application of post-combustion control methods such as the proposed HELPS device. Reducing furnace energy consumption can be effected by new burner/combustion chamber designs, more efficient heat exchanger designs, and devices installed in the flue for heat loss prevention and heat recovery, such as the proposed HELPS concept.

4.1 EMISSION REDUCTION METHODS AND RESEARCH PROGRAMS

The three major options for reducing pollutant emissions from combustion sources include fuel substitution, combustion process modification, and post-combustion control. As described in Section 3 of this report, the majority of residential furnaces are fueled by either natural gas or distillate oil. Fuel switching (to gas) would logically be applied only to oil-fired furnaces, mainly for particulate abatement. However, the associated equipment conversion required by such a move would be economically unfeasible. This leaves combustion and post-combustion control as the most viable means for achieving emission reduction goals.

Reducing emissions generated in flames by modifying the combustion process itself has, in recent years, gained popularity as a NO_x control strategy for industrial and utility boilers. The same principles can be applied on a much smaller scale but with equal validity to residential heating systems. As with the larger scale combustion equipment, care must be taken to avoid emissions trade-off problems, that is, increasing one pollutant species due to a control aimed at reducing another.

The important combustion control emission reduction strategies include:

- Excess air level adjustment
- Modification of combustion chamber design

- Installation of flame retention burners
- Ignition system condition
- Regular service and maintenance

Descriptions of these control options appear in Table 4-1, with comments describing the relevant effect of each option.

The second alternative available for reducing undesirable furnace emissions is the treatment of the combustion product gases, usually by a retrofit device installed in the flue. Most of the candidate devices are designed to abate a single pollutant, and combinations of them may be used for multiple pollutant species reduction.

The principle types of flue gas treatment (FGT) devices for possible application to home heaters include the following:

- Spray tower
- Packed tower
- Fabric filter
- Activated charcoal filter
- Cyclone
- Combinations of devices

Table 4-2 describes these devices in greater detail. As will be discussed in Section 5 of this report, the proposed HELPS device incorporates both the spray tower and the packed tower concepts.

In general, the feasibility of most of these devices for residential heating applications is unknown. Most would entail considerable capital and installation expense. In the event that the application of an FGT device became mandatory, those concepts featuring heat recovery as well as emission control will be the most attractive. Examples of such devices are the spray tower and the packed bed., both of which involve the direct contact of water with the flue gas. The versatile design of the experimental HELPS device described in Section 5 of this report will allow for the investigation of both configurations.

There is a significant amount of industry-sponsored and government-sponsored research and development effort currently being expended in the area of reducing emissions from residential heating equipment. These activities are described in Table 4-3.

TABLE 4-1. COMBUSTION CONTROL STRATEGIES

Control Strategy	Impacted Pollutant Emission	Comments	References
Excess air level adjustment	NO	• As excess air is increased, CO, HC, and smoke pass through a minimum, but NO_x passes through a maximum. • Optimum pollutant and thermal efficiency level occurs at a stoichiometric ratio greater than one (≈1.6 for oil burners).	13, 14, 16
Combustion chamber design	NO CO HC Smoke/particulate	• Combustion chamber design affording long residence time at high temperature minimizes smoke, particulates, CO, HC, but may increase NO_x. • Refractory-lined chamber affords better combustion and lower emissions.	14, 16, 17
Flame retention burners	Smoke	• Oil burners with retention-type end cones can give superior emission and efficiency performance. • Most devices increase NO_x.	14, 16
Ignition system condition	NO	• No effect on HC and smoke. • Minimal effect on NO_x.	14, 16
Service and maintenance	NO CO HC Smoke/particulate	• Equipment state-of-repair very important for providing breadth for reducing emissions by other methods. • Oil nozzles should be changed each season. • Air filter should be replaced regularly	13, 14, 16

TABLE 4-2. POST-COMBUSTION CONTROL DEVICES

Control Strategy	Impacted Pollutant Emission	Comments	References
Spray tower	Smoke/particulate	• Gas sprayed with scrubbing fluid inside closed vessel. • Some industrial uses, but feasibility for residential furnaces yet to be determined. • Direct contact feature allows for simultaneous heat recovery (HELPS)	19, 21, 22
Packed tower	Smoke/particulate, hydrocarbons (HC)	• Gas contacted with scrubbing fluid on surface of special packing inside closed vessel. • Proven particulate and odor removal method. • Applicability for residential use not yet determined. • Direct contact feature allows for simultaneous heat recovery (HELPS).	23, 24
Fabric filter	Smoke/particulate	• Filter is porous to gas but barrier to particulate. • Most high efficiency filters not designed for typical furnace flue gas temperatures. • Excessive ΔP (~1" W.C.). • No simultaneous heat recovery feature.	18, 19, 20
Activated charcoal filter	Odor, HC	• Hydrocarbon absorbed by charcoal • Used frequently to remove odors and solvent aerosols • Max. temperature = 100°F; may be practical for furnace flue gas treatment if stack temperature can be reduced. • No simultaneous heat recovery feature.	19, 25, 26
Electrostatic precipitator (ESP)	Smoke/particulate, odor	• Charged particles collected on series of parallel plates of opposite charge. • ESP's designed for commercial/residential air filtering not usable at high temperatures found in stacks (plates warp). • Particle agglomeration on plates possibly a problem. • No known ESP specifically designed for residential furnace use. • No simultaneous heat recovery feature. • Very expensive.	27, 28, 29, 20, 30
Cyclone	Particulates	• Centrifugal acceleration in a conical vessel separate particulate from gas. • Feasibility for residential use unknown. • No simultaneous heat recovery feature. • Mildly expensive	22, 27
Combinations of devices	Particulates, HC	• Three step system: – Roughing filter – ESP for fine particulate – Activated charcoal for HC • System this elaborate probably not warranted. • No simultaneous heat recovery feature.	

TABLE 4-3. PRINCIPAL CURRENT OR RECENT RESIDENTIAL EMISSION REDUCTION R&D EFFORTS

Agency and/or Organization	Investigated Pollutant(s)	Nature of Study	References
EPA, RTP	NO_x CO^x HC Smoke/particulates	• Define major emission level control variables. • Recommended emission minimization methods through combustion controls. • Status: Continuing.	14, 16
Battelle, Columbus Labs	NO_x CO^x HC^x Smoke/particulates	• Field investigation of emission from oil-fired equipment. • Found serious emission trade-off difficulties if tuning to low smoke level performed without monitoring instrumentation. • Made comparisons of measured emissions with EPA emission factors. • Status: Final report submitted June 1973.	13
Walden Research Corporation		• Study of Air Pollution from Intermediate Size Fossil-Fuel Combustion Equipment. • Status: Final report submitted July 1971.	17
American Gas Association (sponsor): • Institute of Gas Technology (IGT)	NO_x	• Study of fundamental mechanisms of the formation and suppression of NO_x in natural gas combustion. • Not strictly concerned with residential heating units, but results will be relevant. • Status: Ongoing.	
• The Research Corporation of New England (TRC)	NO_x SO^x CO^x HC Smoke/particulates	• Measuring the environmental impact of domestic gas-fired heating systems. • Emissions being related to ambient air quality. • Status: Ongoing (through 1973-74 heating season).	31
Rocketdyne	NO_x CO^x HC Smoke/particulates	• Optimized burner/firebox for oil-fired residential furnace. • Status: On going.	32
Aerotherm/ Acurex	NO_x CO^x HC Smoke/particulates	• Study of feasibility of a simultaneous heat and emission loss prevention system for area source furnaces (HELPS). • Status: Phase I final report completed 1974; investigation of particular concepts ongoing.	1

At the present time it is difficult to determine the optimum method of reducing emissions from residential furnaces. Combustion control methods, such as lowering excess air, are effective but limited by the typically crude and simple burner designs found in residential furnaces. An optimized burner/combustion chamber shows promise, but is expensive and applicable only to entirely new furnace designs. Post-combustion control methods such as the FGT devices tabulated previously can be unduly complicated in configuration and operation, but some designs offer the added benefit of reducing energy consumption by recovering heat from the flue gas. The subject of energy efficiency is covered in an overall sense in the following sub-section of this report.

4.2 ENERGY CONSERVATION METHODS

There are, at present, many programs being conducted aimed at reducing residential energy consumption. These efforts are being spearheaded by both government agencies and industrial associations, such as the Department of Housing and Urban Development (HUD) and the American Society of Heating, Refrigeration, and Ventilation Engineers (ASHRAE), respectively. Table 4-4 lists a number of these ongoing programs involved in various aspects of energy conservation in the residential sector.

The objectives of these programs, like the major energy conversation strategies themselves, can be divided into two basic categories:

- Reduce energy consumption by architectural modification
- Reduce energy consumption by alteration of the energy conversion system.

The first topic considers such improvements as will prevent heat loss from the heated space after it has been generated by the energy conversion system. This includes insulation of walls, ceiling, and heating ducts as well as more "energy efficient" building designs. This subject is not covered in this report. The HELPS program is intrinsically related to the second energy conservation strategy.

Alteration of the energy conversion system, or fossil fuel-fired furnace in this case, can be effected by the following options:

- Modification of the burner and the combustion chamber
- A more efficient heat exchanger design
- Preventing heat loss through the flue during the off-cycle
- Recovering heat from the flue gas.

TABLE 4-4. STUDIES IN CONSERVATION OF ENERGY FROM RESIDENTIAL BUILDINGS

Agency/Association/Institution	Nature of Studies
U.S. Department of Commerce Bureau of Standards – Center for building Technology	• Computer analysis of building thermal response • Importance of insulation • Fenestration and infiltration • Equipment and system options • Heat pumps • Heat exchangers • Underground heat distribution systems • Field demonstration projects using energy conversation projects • Total energy systems • Publication of relevant energy conservation information • Workshops on energy conservation • Recommendation of standards
U.S. Department of Housing and Urban Development – Office of the Assistant Secretary for Policy Development and Research (Support from NSF-RANN and EPA) (Hittman Associates)	• Identify means for obtaining greater efficiencies in the consumption of residential power • Quantify total energy balance in typical residence • Identify technical innovation to reduce residential energy utilization • Determine the total annual energy savings possible for several modified versions of the characteristic house incorporating energy conservation modifications • Evaluate heating loads in old residential structures
– Building Technology and Site Operations (California State Polytechnic University)	• Research and evaluation of a system of natural air conditioning with solar energy as the power source
National Science Foundation/RANN – Center for Environmental Studies, Princeton University	• Research project entitled Energy Conservation in Housing – Statistical study of a large multiple family dwelling to determine distribution of energy utilization – Development of data acquisition system – Surveillance of the construction of townhouses and apartments – Interview and discussion with developers to develop ideas for improvement for energy utilization
– Oak Ridge National Laboratory U.S. Atomic Energy Commission	• Estimate potential monetary and energy savings through the use of additional thermal insulation in residential construction • Develop inventory of current energy research and development
– California Institute of Technology, Environmental Quality Laboratory	• Solar/thermal technologies for buildings – technical, economic and institutional aspects • Project SAGE – a project to investigate the commercial feasibility of solar assisted gas energy for water heating in new apartments. Update ASHRAE Guide and data book to reflect latest technology on conservation of energy. Provides component index of technical articles published by the Society and presented in the Journals.
– ASHRAE Standard 90-P Committee	• Has taken the NBS document on design and evaluation criteria for energy conservation mentioned above and drafted an ASHRAE Interim Standard on Energy Conservation for use by the National Conference of States on Building Codes.

TABLE 4-4. (Continued)

Agency/Association/Institution	Nature of Studies
Long Island Lighting Company	• Electric energy utilization study of the generic environmental impact of electric versus oil space heating, i.e., what effect electric heat will have on air quality
Stevens Institute of Technology	• Determine efficiency fuel oil burners in the field and difference between makes. • Determine method of maintaining efficiency
Pennsylvania Power and Light Company – Franklin Institute Research Laboratory	• Assist in the design of energy conserving home incorporating features such as heat pumps, waste heat recovery, supplementary solar heating and thermal energy storage • Construction and testing of the above house
Consolidated Natural Gas Service Company (Thermo-Electron Corporation)	• Development of a compact liquid heater for industrial and commercial heat transfer applications
Oklahoma Gas and Electric Company	• Development of a computer oriented system for determining building energy requirements and an economic analysis of their equipment
Southern California Gas Company – Thermo-Electron Corporation	• Similar to above; development and distribution of E cube computer program to determine energy consumption of a building. Also sponsored by A.G.A. • Application of heat pipe technology to appliances
Environmental Protection Agency – Office of Research and Monitoring	• Conducted study of various strategies for reducing national energy
– Rocketdyne (contractor)	• Development of optimum oil-fired burner and furnace package
– Aerotherm/Acurex (contractor)	• HELPS
– Battelle Columbus Laboratories	• Investigation of thermal fatigue of heat exchangers in domestic gas furnaces • Indoor air quality control device
– Thermo-Electron Corporation	• New development in gas fired applications; application of Rankine cycle engines to residential gas air conditioning
– AiResearch Manufacturing Company	• Development of a heat actuated space conditioning unit for commercial applications – utilization of a Brayton cycle engine
Pope, Evans and Robbins	• Economic advantage of central heating and cooling systems
University of Oklahoma Research Institute/ Public Service Company of Tulsa	• A comparative study of energy usage
American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) – Edison Electric Research Corporation (York Research Corporation)	• Measurement of the performance of the ASHRAE infrared space heating system • Determination of specific heats of building materials
– University of Florida	• Determination of shading coefficients for reflective coated glasses with draperies
– ASHRAE Research and Technical Committee, Task Group on Energy Conservation	• A task group on energy conservation has been established to evaluate the manner in which basic energy sources can be conserved through the more effective utilization of energy in residential commercial institutional and industrial buildings. Conducts symposia, publishes papers by members.
– American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)	• Preparation and publication of a ASHRAE Guide chapter on application of solar energy for heating and cooling of buildings

TABLE 4-4. (Concluded)

Agency/Association/Institution	Nature of Studies
– Carneige-Mellon University	• A selective total energy system for a residential complex
American Gas Association – Institute of Gas Technology	• Detailed energy usage profile in test homes • An assessment of selected heat pump systems
– Allied Chemical Corporation	• Absorption heat pump program • New working fluids for Rankine cycle residential air conditioning system • New heat pump working fluids
– K. Johnson Company	• Thermal refrigeration – direct conversion of heat energy into refrigeration
– Ohio University	• Free piston stirling engine driven – gas fired air conditioner
– Dynatech Corporation	• Basic research in heat transfer
– A.G.A. Laboratories	• Design of domestic appliances to use gas at elevated pressures • Development of a central heating furnace with ultra high efficiency (submerged-pulsed combustion device)

The first option is described in Reference 32 and shows promise if the economic and manufacturing barriers can be overcome. The initial HELPS study performed by Aerotherm (Reference 1) identified several improved heat exchanger concepts as well as a computer-assisted methodology for operating them. New heat exchanger designs are, however, applicable only to new furnace units and, in any case, will be met with resistance from budget-conscious manufacturers. The third option deals with the installation of a special butterfly valve in the flue that is designed to close during the off-cycle and prevent furnace cooling. This method was also discussed in Reference 1, as was the fourth one. This last option is the subject of the present report.

The advantages of recovering heat from the flue gas are substantial. Table 4-5 shows the estimated annual energy savings by the incorporation of various energy conservation modifications. This shows that in terms of saving energy, recovery of heat from the furnace flue represents the largest single contribution. This figure of 28 percent, however, includes recovery of both the latent and sensible heat in the flue gas, an accomplishment not realized by such devices as shown in Figure 4-1. The heat pipes draw the heat toward a small fan which expels the warm air into a duct. This noncondensing heat recovery device can save about 9 percent of the heating load and only about 4 percent of the total energy consumption of the house.

Condensing heat recovery devices offer significant advantages. Depending on the flue gas temperature, 30 to 50 percent of the flue gas energy that is available for recovery is from the latent heat of vaporization of the water in the products of combustion. Thus, to realize a significant heat recovery, particularly with the higher efficiency, lower exhaust temperature furnaces that are found in large number of homes, a condensing system will be required.

The design of such a system is dependent mainly on the medium with which the flue gas exchanges heat. This medium may be one or more of the following:

1. Combustion air (air pre-heat)
2. Fuel (fuel pre-heat)
3. Recirculating house air or water exiting from the furnace
4. Recirculating house air or water returning to the furnace
5. Independent air or water system
6. Air intermediary fluid which eventually exchanges heat with one of the other media ("runaround" system).

TABLE 4-5. ENERGY SAVINGS FROM MODIFICATION OF CHARACTERISTIC FURNACE AND BUILDING DESIGN (Reference 33)

Item	Load	
	Percent Saved	10^3 Btu Saved
Furnace Reference Load	100.0	101.0
Flue Gas Heat Recovery	27.9	28.3
Furnace Pilot Elimination*	3.4	3.5
Storm Windows	15.8	16.0
25% Window Area Reduction	19.1	19.4
Cinder Block Insulation	7.1	7.2
High Capacity Wall	2.6	2.6
Sealed Furnace Air Supply	4.6	4.7
Sealed Hot Water Air Supply	1.7	1.7
Clothes Dryer Recovery	2.4	2.4
Double Door Design	1.6	1.5
Revolving Door Design	2.6	2.7

*Based on a 1000 Btu/hr pilot light.

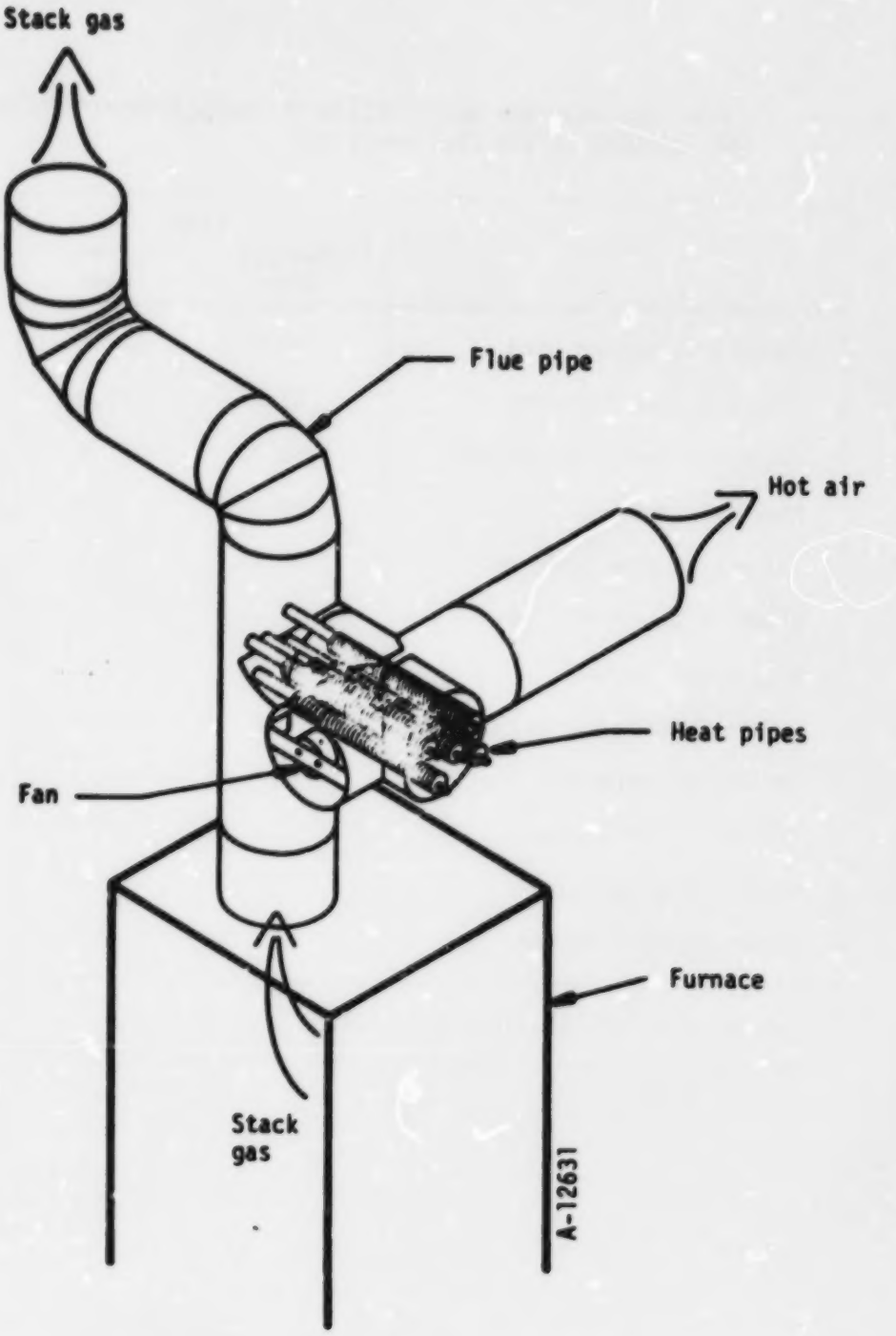


Figure 4-1. Noncondensing flue gas heat recovery device (after Isothermics, Inc.).

The advantages and disadvantages of each of these approaches are tabulated and ranked subjectively (according to probability of success) in Table 4-6.

Although the method 6 "runaround" circuit shows a fairly high potential, the cost is probably greater, except for the heat pipe approach, than for schemes 3, 4, and 5. The disadvantages of methods 1, 3, and 4 appear to outweigh their advantages, and scheme 2 can be dismissed because the heat capacity of the fuel within the temperature limitation of the flue gas is a small fraction of the potential heat recoverable.

By all counts, method 5 affords the most advantages, including versatility and the potential for condensing heat exchange. In addition, the goals of the HELPS program can be achieved by using a wet scrubber device based on method 5. The conceptual design of this unit is described in Section 5 of this report.

4.3 SUMMARY

Methods for reducing emissions from residential furnaces can be modeled after those used successfully on larger units, such as utility boilers. These methods fall into three basic categories: Pre-combustion, post-combustion, and combustion control methods. The fuel switching operation dictated by the first strategy is impractical and costly. Combustion control methods consist mainly of burner maintenance, tuning, and improved burner design. These strategies have been quite successful, but it has been shown in many cases that emissions of oxides of nitrogen increase when tuning for optimal thermal efficiency. Tuning is, in any case, limited in scope due to the crude and simple burner designs found in residential furnaces.

Post-combustion control methods for residential furnaces have not yet been investigated. These include such devices as spray and packed towers, filters, electrostatic precipitators, and cyclones. The latter three are not well suited for the type of fine particulate generated by an oil-fired residental furnace and would be useless on a gas-fired furnace. Wet devices such as the spray and packed towers have the potential for removing both particulate and gaseous emissions.

The number of studies concerned with emission reduction is far outweighed by the number aimed at reducing energy consumption in the residential sector. These efforts are being led by both government and industry. The objective of these programs, like the two major energy conservation strategies themselves, can be divided into two basic categories:

- Reduce energy consumption by architectural modification
- Reduce energy consumtpion by alteration of the energy conversion system.

The present study concentrates on the latter strategy.

TABLE 4-6. FLUE GAS HEAT RECOVERY SCHEMES

Scheme Number	Exchange Flue Heat With	Advantages	Disadvantages	Rank*
1	Combustion air	• Equal mass flow rates • Room air (low temperature) available for heat exchange • Low temperature duct work	• Preheated combustion air may produce excessive furnace metal temperatures • Require extensive duct work • May not be compatible with a naturally aspirated gas burner or oil burner	5
2	Fuel	• Compact heat exchanger • Easy retrofit	• Heat capacity of oil or gas is fraction of available within temperature restrictions	6
3A	Hot Air from furnace (warm air furnace)	• Flue stream and air stream are parallel and adjacent in up flow design • Possibly can get by without auxillary air fan	• Potential for heat recovery limited to noncondensing case due to ∿ 140 air temperature • Will decrease main air flow rate	4
B	Hot Water from furnace (hydronic system)	• Simple piping • Does not require auxillary pump	• Potential for heat recovery limited to noncondensing case due to 180 water temperature • May decrease total water flow rate	
4A	Cold Air to furnace (warm air furnace)	• Potential for condensing heat exchance • May not require auxillary fan	• Required extensive duct work reventing • May decrease main air flow rate	3
	Cold Water to furnace (hydronic system)	• Simple piping • Potential for condensing heat exchange • Does not require auxillary pump	• May decrease main water flow • May not be compatible with a hydronic system	
5	Independent air/water stream	• No change to main air ducting • Can choose air/water flow for optimum heat exchanger design • Does not affect main air/water flow rates • Probably least expensive scheme • Can run duct to spare room, garage, basement, etc. or back into main air stream if pressures compatible • Potential for condensing heat exchange	• Requires auxillary fan or pump • In some case would require extensive separate duct work or piping	1
6	Intermediary Fluid ("Runaround Circuit")	• Least possibility for leakage of gas/air streams • Simple manifolding – can run streams in parallel • Ideal for heat pipe • Potential for heat sink remote from heat source	• Except for heat pipe, requires auxillary "runaround circuit" and equipment (pump, valves piping, etc.)	2

*1 = best
6 = worst

Modification of the energy conversion system, or furnace in this case, can be accomplished by changing the combustion equipment (i.e., burner and combustion chamber), new heat exchanger design, closing the flue during the off-cycle, and recovering heat from the flue gas. The latter method affords the greatest benefit. If both latent and sensible heat are recovered from the flue gas, an evergy savings of 28 percent will result. Recovering latent heat dictates, however, that the device be a condensing heat exchanger.

The device described in Section 5 of the present report will meet this requirement. The wet scrubber concept will cool the flue gas far below the condensation point to ensure maximum heat recovery. In addition, the goals of the HELPS program, that of concurrent heat and emission recovery, can be achieved at least conceptually by using a direct contact device.

SECTION 5

THE HELPS CONCEPT

The preceding sections of this report reviewed residential heating technology, in terms of both equipment design and the available options for reducing emissions and energy consumption. Some of these options have already been investigated in laboratories, and partial success has been achieved. Other methods, as yet untried, appear to have a large potential for saving energy by recovering waste heat. One of these, the direct contact heat and emission loss prevention system, abbreviated HELPS, will act to simultaneously reach both the energy and emissions objectives. This section of the present study will describe this concept in greater depth by discussing the following topics:

- Design of HELPS device
- HELPS benefits – national emission reduction and oil savings
- HELPS costs – retrofit economics for typical American home.

The basic calculations from which these results derive comprise this report's Appendix.

5.1 DESIGN OF THE HELPS DEVICE

The design conditions for the HELPS device are given in Table 5-1. These figures are the results of the calculations in Appendix A. The oil-fired furnace burns 100,000 Btu/hr of fuel at a nominal efficiency, set by the American Gas Association, of 80%. The bulk of the remaining 20 percent goes out the flue. The sensible heat of the flue gas is increased by the latent heat of vaporization of the water in the combustion products.

The flue gas is composed mostly of CO_2, H_2O, O_2, and N_2. As given previously in Table 3-7, EPA emission factors are used to determine the pollutant species flow rates, given in Table 5-1 in units of lb/hr.

Table 5-2 gives the HELPS device's design and performance characteristics. Appendices B and C contain the calculations used to derive these data. The device will be cylindrical in shape and operate as a spray or packed tower. Figures 5-1 and 5-2 show these configurations. The test program described in Section 6 of this document will determine which of the two designs is superior.

TABLE 5-1. HELPS DEVICE DESIGN CONDITIONS

Furnace heat release rate	100,000 Btu/hr	
Furnace efficiency (Nominal)	80 percent	
Furnace fuel flow rate	0.75 GPH	
Furnace excess air	60 percent	
Flue gas enthalpy	20,650 Btu/hr	
Flue gas temperature	500°F	
Flue gas density	0.04127 lb/ft^3	
Flue gas flow rate	52 ACFM	
Major flue gas components	Vol.%	lb/hr
CO_2	8.77	17.07
H_2O	7.96	6.34
O_2	7.55	10.69
N_2	75.72	93.8
	100.00	127.9
Pollutant flue gas components	10^{-3} lb/hr	
CO	3.75	
NO	11.53	
NO_2	1.97	
SO_2	31.95	
SO_3	0.45	
HC	0.75	
Particulate	1.875	
	52.275	

TABLE 5-2. HELPS DEVICE DESIGN AND PERFORMANCE CHARACTERISTICS

General shape	Cylindrical
Operation principle	Spray and packed tower
Height	18"
Diameter	10"
Materials of construction (production item)	PVC plastic
Scrubbing water flowrate	0.5 GPM (0.05 GPM makeup)
Scrubbing water inlet temp. and pressure	50°F, 40 psig
Scrubbing water outlet temperature	120°F
Flue gas inlet temperature	500°F
Flue gas outlet temperature	80°F
Flue gas enthalpy	20,650 Btu/hr
Heat recovered	17,350 Btu/hr
I.D. fan power (1/8 hp)	320 Btu/hr
Net heat recovered	17,030 Btu/hr (84 %)
Overall furnace system efficiency	97%
Pollutant removal efficiency:	
Particulate	90-95% over 1μ (by weight)
NO_2, SO_3, HC	~90%
CO, NO, SO_x	~0%

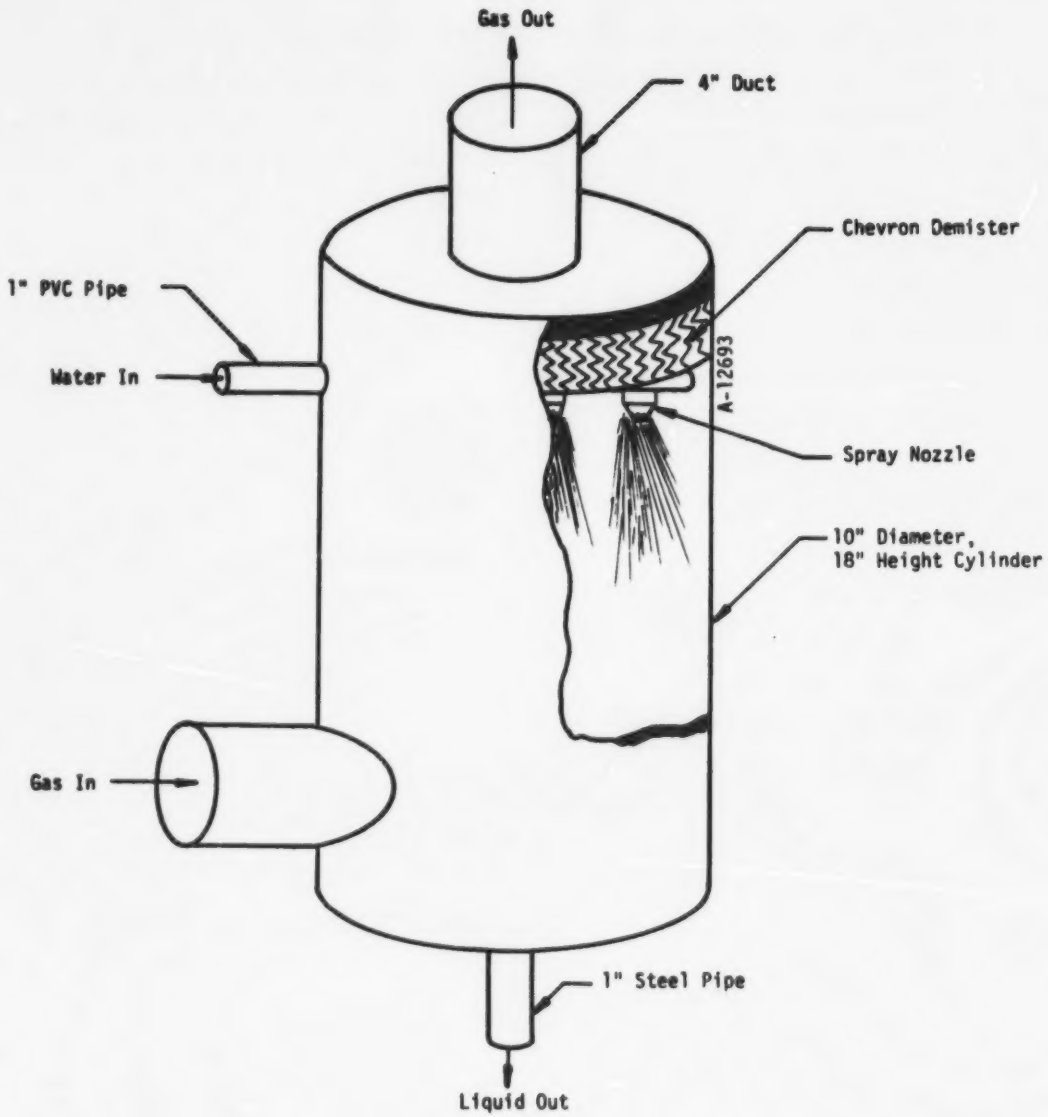


Figure 5-1. Spray tower HELPS device.

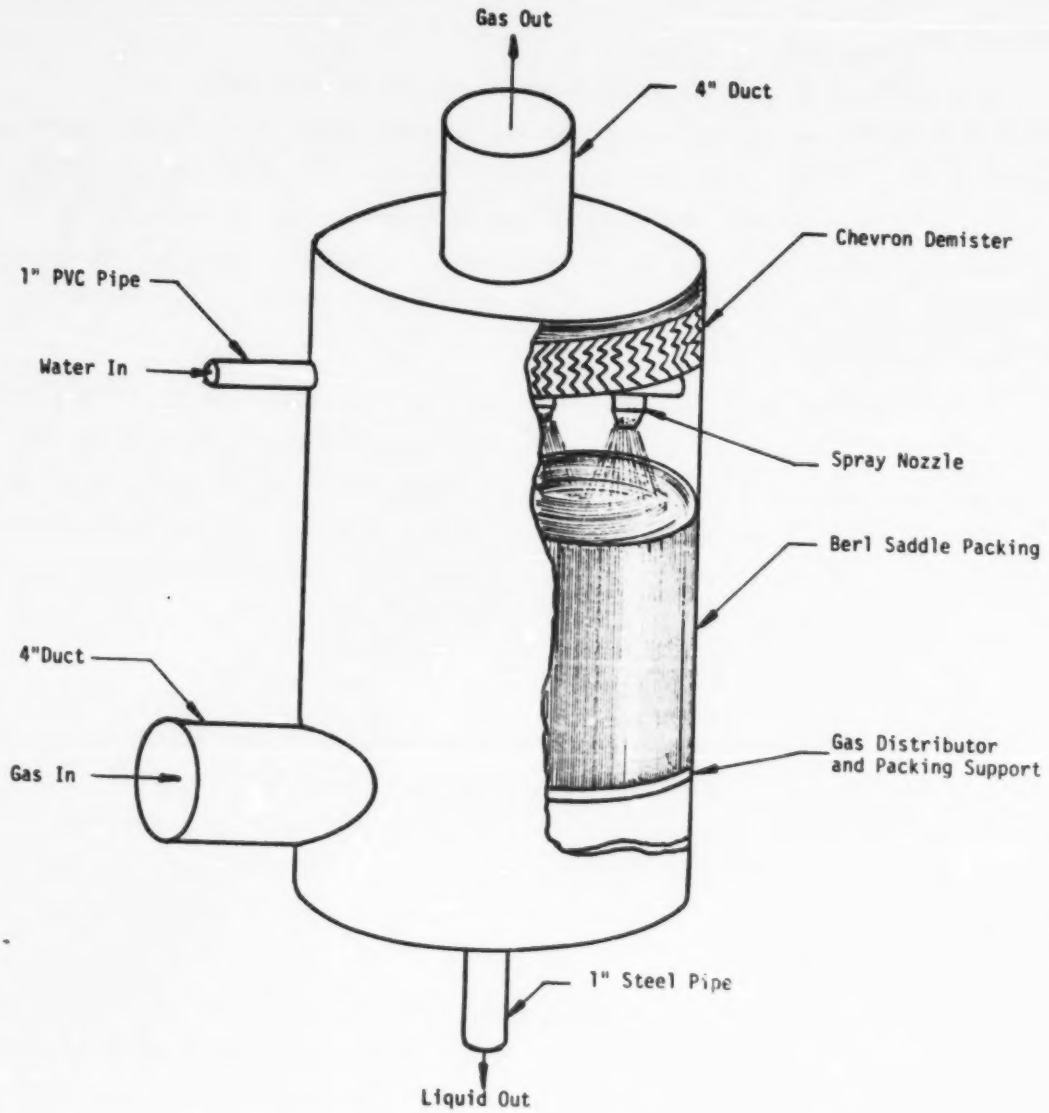


Figure 5-2. Packed tower HELPS device.

Although the mass-produced HELPS device will be fabricated from economical PVC plastic, the prototype, described in the following section of this report, will use a length of 10-inch steel ducting.

In practice, the HELPS device and the small I.D. fan will be installed in the flue of the existing home furnace, and water connections made with the home system. The device will recover about 84 percent of the heat in the flue gas, which will increase the overall furnace system efficiency to almost 97 percent. Of course, some practical means of using the recovered heat, such as routing the hot water through a separate air-cooled radiator, must be devised before this increase in efficiency can be relaized. Such schemes will be identified during the test program described in Section 5.

It is assumed that over 90 percent removal efficiency of particulate over 1μ will be achieved by the HELPS device. Assuming good contact, solubility dictates that almost all of the NO_2, SO_3, and unburned hydrocarbons will be removed from the gas stream, while virtually none of the CO, NO, and SO_2 will be absorbed by the scrubbing water. Again, the lab facility described in Section 6 will test these assumptions with the combination of a full-scale residential furnace and a versatile, prototype HELPS device.

5.2 HELPS BENEFITS

The reductions in emissions and energy consumption associated with the HELPS device will be significant. As shown in Table 5-2 the device is assumed to be almost 100 percent effective in collecting NO_2, SO_3, and unburned hydrocarbons, and 90 percent efficient on particulate over 1μ. The corresponding uncontrolled emission estimates given in Table 3-8 for these pollutant species are 4.66×10^7 lb/yr (assuming $NO_x/NO_2 = 0.1$), 5.2×10^6 lb/yr (assuming S = 0.1 percent), and 6.5×10^7 lb/yr, respectively.

Given the data for total national emissions from combustion of fuel, obtained from the EPA's National Emission Data System (Reference 37), the retrofit of the HELPS device on all oil-fired warm air furnaces and hydronic systems will result in national reductions of 0.22 percent, 0.01 percent, and 0.09 percent for NO_x, SO_x, and particulate, respectively. This information is summarized in Table 5-3.

Although these reduction figures appear small, the following facts will tend to increase the attractiveness of the HELPS device for emission reduction:

TABLE 5-3. EMISSION REDUCTION BENEFITS

Pollutant Species	Total Uncontrolled Residential Emissions (10^7 lb/yr)	HELPS Device Emission Reduction (10^7 lb/yr)	National Total Emissions From Fuel Combustion** (10^7 lb/yr)	Percent Reduction by HELPS (%)
NO_x	4.66 (NO_2)	4.66	2160	0.22
SO_x	0.52 (SO_3)	0.52	5100	0.01
Particulate	6.5	1.17*	1330	0.09

* According to Barrett, et al. (Reference 36), 80 percent of this particulate is < 1μ. Therefore, 20 percent of $6.5 \times 10^7 = 1.3 \times 10^7$, and 90 percent of $1.3 \times 10^7 = 1.17 \times 10^6$

** From Reference 37.

- Most of the distillate oil used for residential heating is burned during approximately 6 months of cold weather. Therefore, when the emission reduction figures are seasonably adjusted, their impact will increase roughly by a factor of 2.
- Reducing emissions from those oil-fired residential furnaces located in densely populated cities will afford added leverage over ambient air quality. The HELPS device will aid the Air Quality Control Regions (AQCR) currently attempting to attain the National Ambient Air Quality Standards (NAAQS), as well as maintaining the air quality for AQCR's that may be in noncompliance in the future.

It must be remembered that the emission reduction figures associated with the HELPS device were estimates based on the performance of larger scrubbers. The actual pollutant control potential of the HELPS concept, and its overall value to the nation in this capacity, can be determined only through a laboratory investigation such as that outlined in Section 6 of this report.

The energy conservation benefit associated with the HELPS device is easier to determine. As mentioned previously, the consumption of distillate oil for residential heating in the United States is equivalent to about 3571×10^{12} Btu/yr. If, according to the previous calculations, the HELPS device effectively increases the overall furnace system efficiency by 17 percent, the resulting energy savings will be 607×10^{6} barrels of distillate oil each year. This corresponds to a national reduction in distillate oil consumption of about 10 percent, and a reduction in the Nation's gross energy consumption of almost 1 percent. This information is summarized in Table 5-4.

Besides the primary benefit of reducing the country's gross energy consumption, reducing the demand for distillate oil for residential heating frees this clean fuel for other uses. Alternately, energy and money can be saved in refinery operations by lowering the production of energy-intensive, expensive distillate oils.

5.3 HELPS COSTS

Pertinant cost figures include the following:

- Capital costs (parts and installation)
- Maintenance cost
- Operating cost
- Fuel savings

TABLE 5-4. ENERGY CONSERVATION BENEFITS

National residential heating distillate oil consumption (10^{12} Btu/yr)*	3571
Approximate furnace efficiency increase from HELPS (%)	17
Reduction in residential fuel usage from HELPS (10^{12} Btu/yr)	607
Equivalent barrels of distillate oil** (10^{6} Barrels/yr)	105
National Consumption of distillate oil*** (10^{6} Barrels/year)	1020
Reduction in distillate oil consumption from HELPS (%)	10.3
National gross energy consumption*** (10^{12} Btu/yr)	68000
Reduction in National gross energy consumption from HELPS (%)	0.9

* Warm air furnace and steam/hot water systems only.

** Based on heating value = 138,000 Btu/gal.

*** 1972 Data, Reference 38.

These quantities are used to determine the payback period of the device. Appendix D contains the relevant cost calculations.

The capital cost of the HELPS device on a mass-produced basis is estimated to be $225. This includes a simple plastic shell, packing (for the packed tower case), spray nozzles, I.D. fan, related piping and controls, and a $25 installation fee. The hardware cost is, of necessity, a rough estimate since scrubber cost calculational methods, such as those found in Reference 35, do not apply to devices as small as the HELPS. The maintenance cost is also an estimate, and will amount to $5.

The operating cost is the sum of the additional water and electricity costs associated with the HELPS device. As mentioned previously in Table 5-2, the water flowrate through the scrubber is 0.5 GPM. Most of this water, however, will be recirculated. It is estimated that make-up water, which compensates for evaporation and the continuous rejection of some of the polluted water, will amount to one-tenth of the total flow through the loop. At a water cost of $0.005 per gallon, this make-up water will cost the resident family an additional $16 per year.

The sum of the water cost and the extra $3 per year needed to run the I.D. fan gives an annual operating cost of $19. With the addition of the annual maintenance cost, the total annual cost amounts to $24. This information is summarized in Table 5-5. The incremental wastewater treatment costs were deemed insignificant in this analysis.

The payback period for the HELPS device must be calculated solely on the basis of the savings in fuel cost, rather than attempting to determine a cost-benefit factor for the devices pollution control characteristics. Due to the rapidly varying cost of energy, calculating a payback period based on a single figure for fuel oil cost cannot be justified. More reasonably, a range of payback time versus fuel cost must be defined. Using the information given in Table 5-6, Figure 5-3 shows how the time required to break even on the cost of the HELPS device varies with fuel cost. No one can, at present, estimate the future cost of heating oil. With present inflation rates, the cost of heating oil ranges from 20¢ to 50¢ per gallon. In any case, the attractiveness of the HELPS device for energy recovery is directly proportional to fuel cost, for which an increasing trend is predicted.

5.4 SUMMARY

The HELPS concept involves the retrofit of a small wet scrubber in the flue of oil-fired residential furnaces. The device would be cylindrical in shape (D = 1 ft, H = 1.5 ft), be fabricated from economical PVC plastic, and include spray nozzles, a chevron demister, packing material

TABLE 5-5. HELPS DEVICE COST

Capital Cost	$225.
Annual Costs	
• Water	$ 16.
• Electricity	$ 3.
• Maintenance	$ 5.
• Total annual costs	$ 24.

TABLE 5-6. PAYBACK PERIOD TABLE (REFERENCE 41)

End of Year	Amount*
1	0.93
2	1.78
3	2.58
4	3.31
5	3.99
6	4.62
7	5.21
8	5.75
9	6.24
10	6.71
11	7.14
12	7.54
13	7.90
14	8.24
15	8.56

*Based on $i = 8\%$

and Amount $= \Sigma \frac{1}{(1+i)^n}$

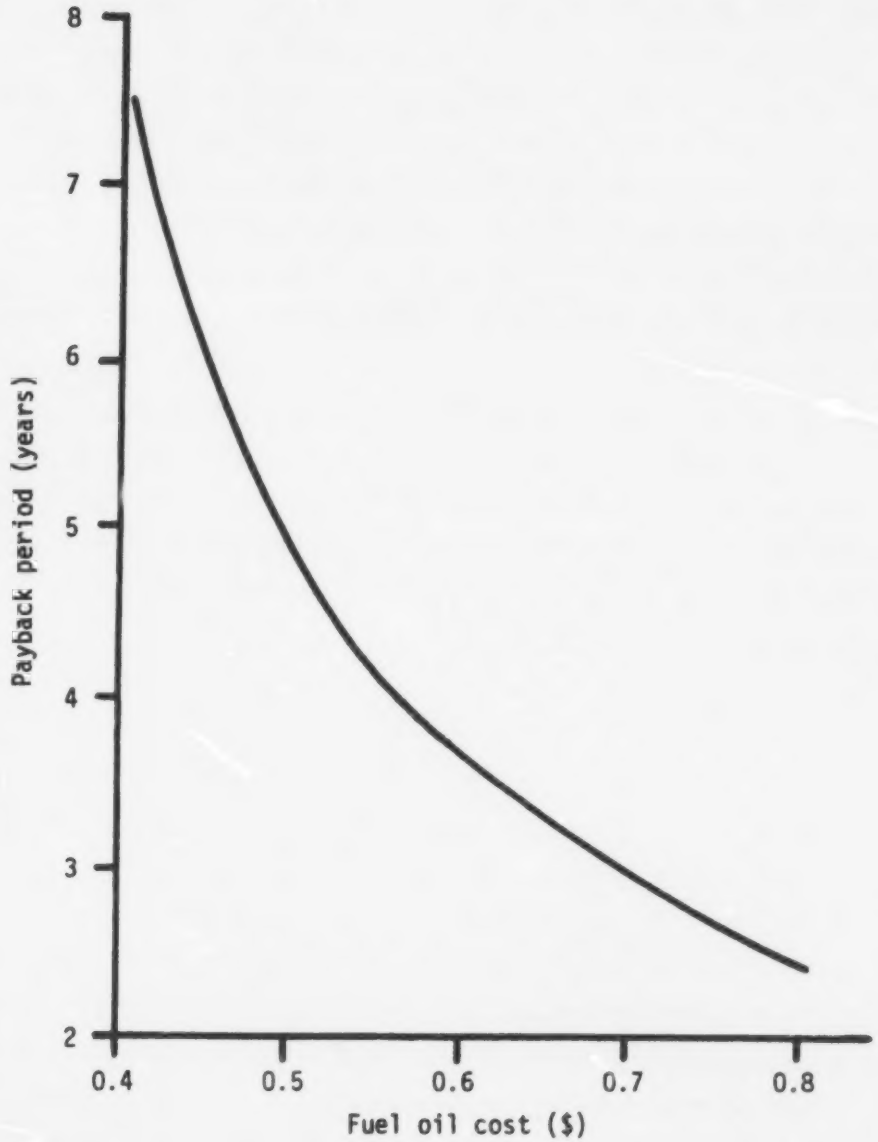


Figure 5-3. Payback period versus fuel oil cost.

(in the case of the packed tower concept), and I.D. fan, and related piping and controls. Table 5-2 gives the HELPS device design and performance characteristics.

Calculations show that the device can recover 84 percent of the heat from 500°F flue gas, bringing the overall furnace system efficiency up from 80 percent to almost 97 percent. This efficiency figure has not been reduced by the increased power requirements for waste water treatment, a figure that was deemed insignificant. Applied to most oil-fired residential furnaces, the HELPS device will achieve a 10 percent reduction in the national consumption of distillate oil, which is equivalent to a 1 percent reduction in the Nation's gross energy consumption. Reducing demand for heating oil frees this clean fuel for other, perhaps more cost-effective uses. Alternately, energy and money can be saved in refinery operations by lowering the production of energy-intensive, expensive distillate oils.

In addition to the energy savings, the device will capture 90 to 95 percent of particulate over 1μ by weight, and virtually 100 percent of the NO_2, SO_3, and unburned hydrocarbon emissions. Although the impact on reducing the nationwide production of these pollutants is small, it is felt that reducing emissions from those oil-fired residential furnaces located in densely populated cities will afford added leverage for the attainment or maintenance of the NAAQS.

The capital cost of the HELPS device, including installation charges, is estimated at $225. This is the retail cost to the homeowner of a mass-produced item. Additional costs for water and electricity amount to a total of $19 per year, while $5 is an estimated maintenance cost. The total annual operating and maintenance cost, therefore, is the sum of these costs, or $24.

Due to the rapidly varying cost of energy, calculating a payback period based on a single figure for fuel oil cost cannot be justified. More reasonably, a range of payback time versus fuel cost must be defined. Figure 5-3 shows how the time required to break even on the cost of the HELPS device varies with fuel cost. In any case, the attractiveness of the HELPS device for energy recovery is directly proportional to fuel cost, for which an increasing trend is predicted.

It must be remembered that the foregoing emission reduction, energy conservation, and cost figures associated with the HELPS device were estimates based on the design and performance of larger scrubbers. The actual benefits and costs to the nation of the HELPS device can be determined only through a laboratory investigation such as that outlined in the following section of this report.

SECTION 6

THE HELPS TEST PROGRAM

The preceding section described the theoretical ability of the HELPS device to clean and recover heat from the exhaust gas of a residential furnace. The calculations showed that the concept is generally feasible. No difficulties are foreseen in building a prototype unit; the design is intrinsically simple. Many unknowns do exist, however, in the operation of such a device. These include its reliability, ease of maintenance, temperature response, pressure drop, and turndown capabilities. These characteristics, as well as the actual effectiveness of the device for emission cleanup and energy recovery, can only be determined empirically. That is, the HELPS unit must be evaluated during operation in the flue of a residential furnace. This section of the present report describes a test program by which this can be accomplished.

6.1 HELPS TEST FACILITY

The feasibility of the HELPS concept can best be determined in a laboratory environment under controlled, but realistic, conditions. Figure 6-1 is a schematic of the proposed lab set-up.

The furnace is a 100,000 Btu/hr oil-fired, forced warm air design manufactured by the Day and Night Company. It has already been purchased by the EPA and is currently stored in the Aerotherm wearhouse. The furnace's combustion products can be routed through the HELPS device or diverted directly to the stack. The facility's major features are given in Table 6-1, and a conceptual drawing of the laboratory set-up is shown in Figure 6-2.

During operation of the facility, the important thermodynamic properties of the flowing media will be measured at strategic location. Temperatures will be measured with a combination of dial thermometers and thermocouples. The measurement locations are given in Table 6-2. Ten thermocouples are arrayed on the surface of the furnace heat exchanger and others are installed at different radii in the flue ducting to determine average temperatures.

Similarly, Tables 6-3 and 6-4 give the locations of the differential pressure measurements and the flow rate measurements, respectively. Most of the readout instruments for these sensors will be located on the control board, as shown previously in Figure 6-2.

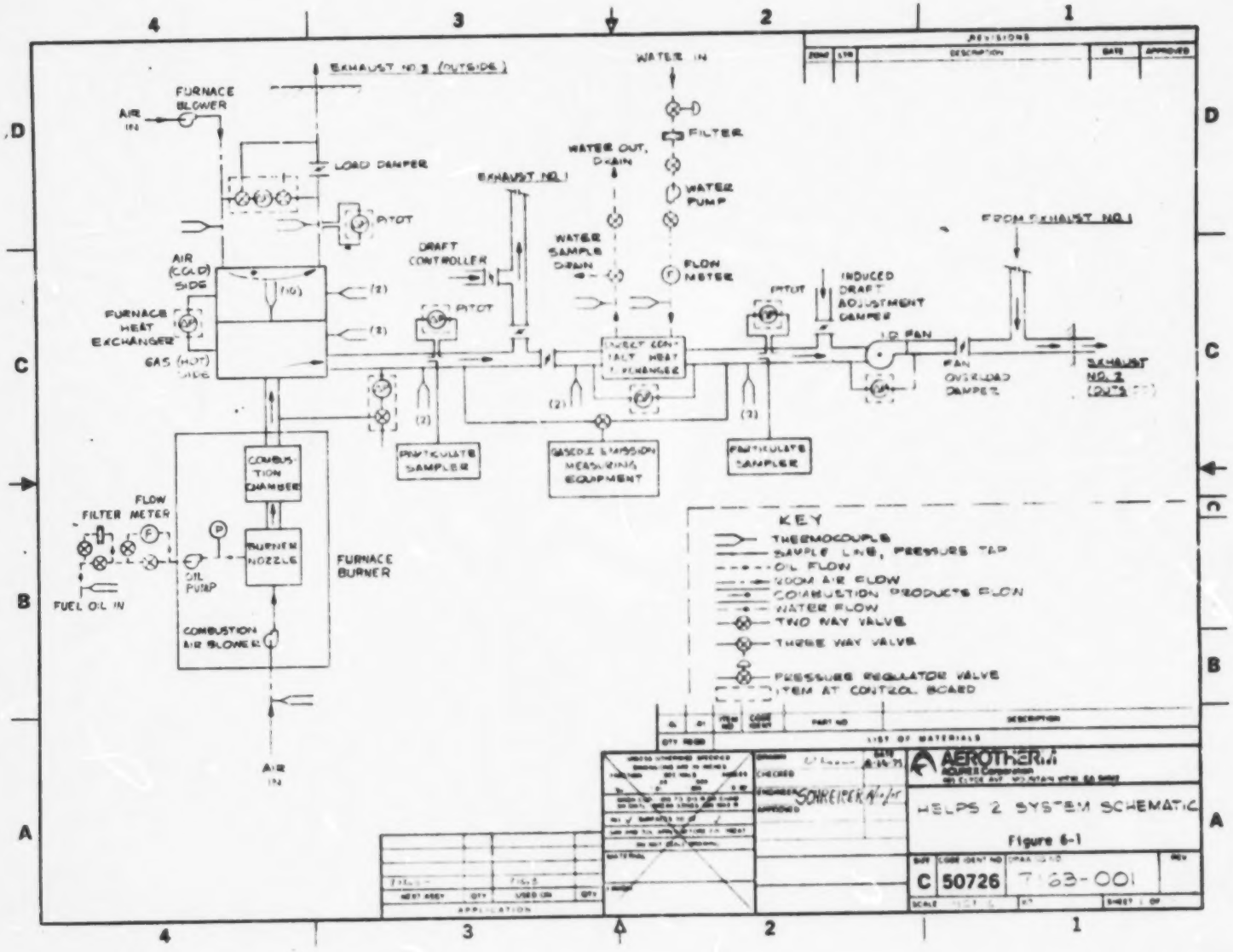
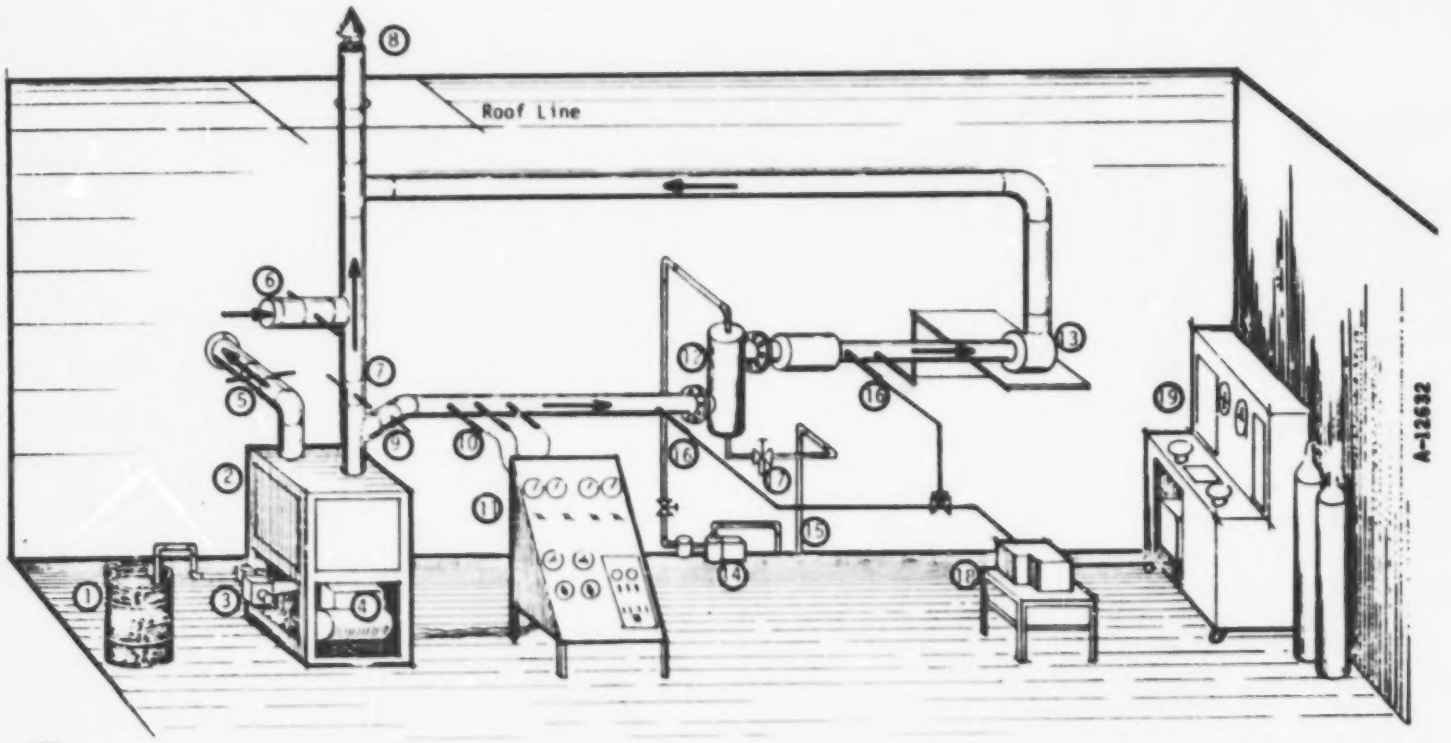

EXHAUST NO 2 (OUTSIDE)
WATER IN
FURNACE BLOWER
AIR IN
FILTER
WATER OUT, DRAIN
LOAD DAMPER
EXHAUST NO 1
WATER PUMP
PITOT
DRAFT CONTROLLER
WATER SAMPLE DRAIN
FLOW METER
FROM EXHAUST NO 1
AIR (COLD) SIDE
FURNACE HEAT EXCHANGER
GAS (HOT) SIDE
INDUCED DRAFT ADJUSTMENT DAMPER
I.D. FAN
FAN OVERLOAD DAMPER
EXHAUST NO. 2 (OUTSIDE)
COMBUSTION CHAMBER
FLOW METER
FILTER
BURNER NOZZLE
OIL PUMP
FUEL OIL IN
FURNACE BURNER
COMBUSTION AIR BLOWER
AIR IN
PARTICULATE SAMPLER
GASEOUS EMISSION MEASURING EQUIPMENT
PARTICULATE SAMPLER
KEY
THERMOCOUPLE
SAMPLE LINE, PRESSURE TAP
OIL FLOW
ROOM AIR FLOW
COMBUSTION PRODUCTS FLOW
WATER FLOW
TWO WAY VALVE
THREE WAY VALVE
PRESSURE REGULATOR VALVE
ITEM AT CONTROL BOARD
REVISIONS
DESCRIPTION
LIST OF MATERIALS
AEROTHERM
HELPS 2 SYSTEM SCHEMATIC
Figure 6-1
C
50726
T 163-001

TABLE 6-1. HELPS TEST FACILITY FEATURES

Item	Features
Furnace	• Oil-fired, warm air, upflow design • Heat release: 100,000 Btu/hr • Oil flow rate: 0.75 gph • Manufacturer: Day & Night • Already purchased by EPA for use in this program; presently stored in Aerotherm warehouse
HELPS design	• Simple, trouble-free design • Cylindrical aluminum cylinder with bottom/top gas inlet/outlet ports • Countercurrent water flow • Designed as spray or packed tower • Integrated chevron demister • Fully insulated exterior surface
Instrumentation	• Temperature measurements - dial thermometer and thermocouples for heat balances on furance and HELPS device • Differential pressure measurements on furnace, HELPS device, and I.D. fan • Flow rate measurement for furnace air and gas sides, furnace oil flow rate, and HELPS device scrubbing water flowrate • Gaseous and particulate emissions sampling and measurement before and after HELPS device
Induced draft fan	• 4" W.C. at 50 acfm • 1/8 hp motor
Butterfly valves	• All have 6", sheet metal, adjustable wafers • Locations: - Furnace warm air outlet load simulator - Two opposed-action valves for diverting flue gas to HELPS device or directly to stack - Draft controller on stack - I.D. fan draft adjustment damper - I.D. fan overload damper
Water pump	• 6 ft head at 50 GPH • 1/35 hp motor • 3/8" fittings



KEY:

1. Oil Drum
2. Furnace
3. Furnace Oil Burner
4. Furnace Blower
5. Warm Air Outlet Butterfly Valve (Exhaust No. 3)
6. Draft Controller Butterfly Valve
7. Exhaust Leg Butterfly Valve
8. Flue (Exhaust No. 2)
9. HELPS Leg Butterfly Valve
10. Sensors (Thermocouples, Pitot Tubes, etc.)
11. Control Board
12. HELPS Device
13. Induced Draft Fan
14. Water Pump
15. Water Drain
16. Emissions Sampling Probe
17. Water Sample Drain
18. Emission Sample Conditioner
19. Emission Sample Analysis Bench

Figure 6-2. HELPS test facility.

TABLE 6-2. TEMPERATURE MEASUREMENTS

Measurement Location	Measurement Method	Number at Measurements
Oil drum	Dial Thermometer	1
Room air inlet	Dial thermometer	1
Room air outlet	Dial thermometer	1
Room air outlet	Thermocouple	1
Furnace heat exchanger surface	Thermocouple	10
Air side, furnace heat exchanger	Thermocouple	2
Gas side, furnace heat exchanger	Thermocouple	2
Emissions sampling location before HELPS device	Thermocouple	2
HELPS device gas inlet	Thermocouple	2
HELPS device gas outlet	Thermocouple	2
Scrubbing water inlet	Thermocouple	1
Scrubbing water outlet	Thermocouple	1

TABLE 6-3. DIFFERENTIAL PRESSURE MEASUREMENT LOCATIONS
(BY MAGNEHELIC GAUGE)

HIgh Pressure Side	Low Pressure Side
Room air inlet	Room air outlet
Room air inlet	Atmospheric
Room air outlet	Atmospheric
Load damper inlet	Load damper outlet
Heat exchanger, air side	Heat exchanger, gas side
Heat exchanger, gas side, inlet	Heat exchanger, gas side, outlet
Atmospheric	Heat exchanger, gas side, outlet
HELPS device gas inlet	HELPS device gas outlet
I.D. fan, outlet	I.D. fan, inlet

TABLE 6-4. FLOW RATE MEASUREMENTS

Measurement Location	Measurement Method
Oil line	Positive displacement meter
Room air outlet	Pitot tube
HELPS device gas inlet	Pitot tube
HELPS device gas outlet	Pitot tube
HELPS device water inlet	Positive displacement meter

Air pollutant emissions will be sampled, conditioned, and measured by Aerotherm's existing instrumentation. The analyzers are described in Table 6-5. The reliability of this console has been verified by its performance in Aerotherm's EPA-sponsored Combustion Research Laboratory.

In all, a high degree of success in the construction and operation of this facility is anticipated. Besides being very simple in concept, the system is devoid of compromising scale-up difficulties; the HELPS device will be tested on the exhaust from a full-size combustion device.

The following subsection outlines a suggested 6 month program to operate the HELPS facility.

6.2 PROGRAM SCHEDULE

Aerotherm recommends a program divided into eight tasks as most appropriate to accomplish the objective of the program. Figure 6-3 shows the schedule of the 6 month project.

The tasks are briefly outlined as follows:

1. Materials procurement

   The parts needed to install and instrument the furnace and the HELPS device will be sought, purchased, and delivered to Aerotherm. The required equipment is listed in Subsection 6.3 of this report.

2. Fabrication of HELPS device

   This task provides for the fabrication of the candidate HELPS device from its component parts procured in Task 1.

3. Furnace installation

   As mentioned in Section 6.1, the oil-fired, warm air furnace has already been purchased by the EPA and is currently stored in the Aerotherm Combustion Research Laboratory. This task will involve the installation of the furnace by a certified installer as well as the instrumentation of the furnace by Aerotherm technicians. The furnace will also be started up and checked for normal operation. This task will be done concurrently with Task 2.

4. Furnace baseline testing

   Before the HELPS device is installed, the furnace's baseline energy and emission characteristics will be determined. The furnace will be optimized for low emission and its thermal efficiency will be determined.

5. HELPS device shakedown testing

   Upon completion of the furnace baseline testing, the HELPS device will be installed in the bypass flue duct. Flue gas will be routed through the device and operation of the

TABLE 6-5. AEROTHERM EMISSIONS MEASUREMENT INSTRUMENTATION

Pollutant Measured	Ranges	Analyzer	Manufacturer
Oxygen	0% - 5% 0% - 25%	Paramagnetic	Beckman F3
Carbon Dioxide	0% - 5% 0% - 15%	NDIR	Intertech URAS-2T
Carbon Monoxide	0 - 500 ppm 0 - 1500 ppm	NDIR	Intertech URAS-2T
Sulfur Dioxide	0-50, 100, 500, 1,000, 5,000 ppm	Fluorescent UV	Thermo Electron 40
Oxides of Nitrogen	1-10, 25, 100, 250, 1,000, 2,500, 10,000	Chemiluminescent	Thermo Electron 10A
Hydrocarbons	10-1,000 ppm	Flame Ionization	Beckman Model 400
Smoke	Bacharach scale	Smoke spot tester	Bacharach 21-7006
Particulate		High volume stack sampler-Gravimetric	Aerotherm/Acurex

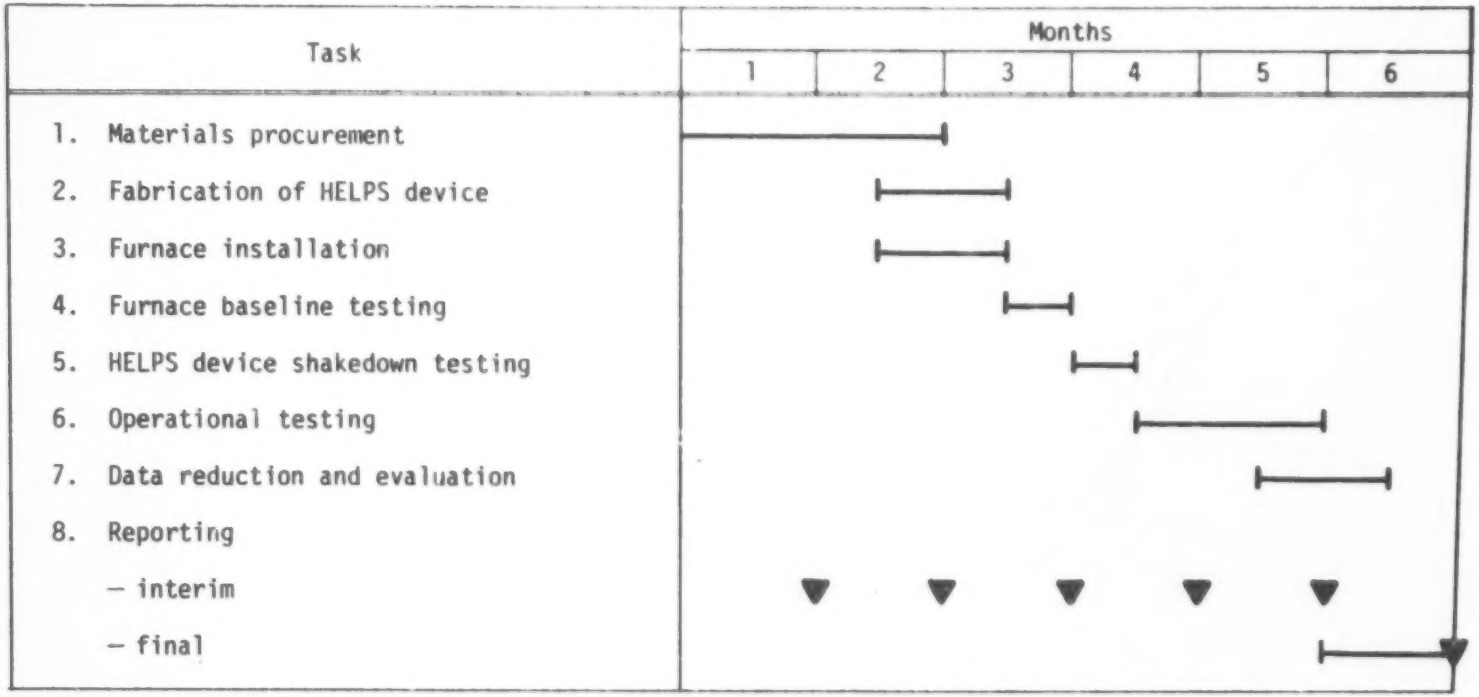


Figure 6-3. HELPS test schedule.

scrubbing water system will be checked. No emissions measurements will be taken at this time.

6. Operational testing

For 1-1/2 months of the 6 month program, the 2 candidate configurations of the HELPS device will be tested. Besides the design of the device (spray or packed tower), the major variables are the flowrates of flue gas and scrubbing water. Both gaseous and particulate flue gas samples will be collected at the inlet and outlet of the cleanup device, and temperatures of the exhaust gas and scrubbing water will be measured at appropriate locations. The quality of the scrubbing water will also be analyzed. Long term tests, with the device subjected to a typical furnace operating cycle, will be conducted.

7. Data reduction and evaluation

The data compiled during Task 6 will be used to determine the heat and emission recovery effectiveness of the 2 HELPS device configurations.

8. Reporting

In addition to the monthly letter progress reports, a final report will be prepared for submittal to the task officer at the end of the sixth month. It will contain a description of the facility and data gathering techniques as well as the program's major results and conclusions.

The following subsection describes the cost to carry out this program by outlining the labor and material requirements.

6.3 PROGRAM MATERIAL COST AND PERSONNEL

A modest quantity of hardware will have to be procured for the HELPS test program. Since Aerotherm currently has an operational combustion research laboratory, some of the material already exists and will be supplied at no cost to the contract. These items are listed in Table 6-6. The remainder of the hardware, listed in Table 6-7, must be procured to complete the test rig.

The labor hours needed to perform the HELPS program are shown in Table 6-8. The hours are assigned to the individual program tasks and cross-tabulated with required personnel. A total of 2,500 hours of combined engineering, technician, and technical publication personnel will be required.

TABLE 6-6. AEROTHERM-SUPPLIED MATERIALS

Item	Quantity
Furnace	
Emissions sampling and conditioning equipment	–
Emissions measurement instrumentation	–
Pyrometer	3
Thermocouple selector switch	3
Oil flow meter	1
Magnehelic gauge	6
Control console raw materials	–
Oil burner test kit	1
Heated teflon sample line	20 ft
High volume particulate sampler	1
HELPS Device	
Water pump	1
Pyrometer	1
Thermocouple selector switch	1
Magnehelic gauge	1
Heated teflon sample line	10 ft

TABLE 6-7. EPA – SUPPLIED MATERIALS (O.D.C.) AND COSTS

Item	Quantity	Unit Cost $	Total Cost $
Furnace			
Furnace installation (certified installer and ducting materials)	–	300	300
Thermocouple assembly	25	20	500
Draft regulator butterfly valve	1	30	30
Butterfly valves	5	25	125
Oil pressure gauge	1	15	15
Cupper tubing	20 ft	0.5/ft	10
Plastic tubing	100 ft	0.2/ft	20
Pitot tube	2	30	60
Oil filter	1	10	10
Two-way ball valve, oil system	4	10	40
Three-way ball valve, ΔP gauges	3	12	36
Two-way ball valves, water system	2	10	20
Three-way ball valves, water system	1	15	15
Cycle simulator (timer)	1	50	50
Tubing fittings	–	50	50
Fuel oil	400 gal	0.4/gal	158
Fuel oil drum deposit	2	15	30
Fuel oil analysis	4 samples	130/sample	520
HELPS Device			
Thermocouple assembly	6	20	120
Water piping and fittings	60 ft	1/ft	60
Raw materials	–	1,000	1,000
Water analysis	–	400	400
Pipe, tubing fittings	–	50	50
Water flow meter	1	80	80
Induced draft fan	1	50	50
	TOTAL =		$3,749

TABLE 6-8. LABOR HOURS

	Hours by Task								
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Task 8	Hours
Engineer	200	400	200	150	150	450	200	250	2,000
Technician	10	40	60	60	60	130	30	10	400
Technical Publication	0	0	0	0	0	0	0	100	100
								Total Hours =	2,500

6.4 SUMMARY

The analysis done previously has proven the theoretical feasibility of using a wet scrubber for concurrently cleaning and recovering heat from the exhaust of a residential furnace. However, the many unknown operational factors associated with the HELPS device must be determined empirically. It is suggested, therefore, that a laboratory investigation be initiated using a typical residential furnace, a prototype HELPS device, and all necessary instrumentation and support equipment.

The laboratory set-up will be simple to construct and operate. Sensor and measurement instruments will obtain energy and emissions data from the furnace and the candidate HELPS device. Much of the required support equipment, most notably the emissions analyzers, already exist in Aerotherm's Combustion Research Laboratory and will be available for use in the HELPS program. Besides being very simple in concept, the proposed facility is devoid of compromising scale-up difficulties; the HELPS device will be tested on the exhaust from a full-size combustion device.

Aerotherm recommends a program divided into eight tasks as most appropriate to accomplish the objectives of the program. They are:

- Materials procurement
- Fabrication of HELPS device
- Furnace installation
- Furnace baseline testing
- HELPS device shakedown testing
- Operational testing
- Data reduction and evaluation
- Reporting – iterim and final report.

The duration of the program will be 6 months.

Some of the required hardware will be supplied by Aerotherm; additional items, costing about $3,700, will have to be purchased to complete the test rig. A total of 2,500 man-hours of combined engineering, technician, and technical publication personnel will be required.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

This document has described a proposed technique for simultaneously reducing air pollutant emissions from, and energy consumption of, residential furnaces. This method consists of a direct contact device, or wet scrubber, that is installed in the furnace's flue pipe. The water that is sprayed on the exhaust gas will collect both particulate and soluble combustion products, as well as recovering most of the heat in the flue gas thereby effectively increasing the efficiency of the furnace system. This concept is abbreviated HELPS, which stands for Heat and Emission Loss Prevention System.

Besides characterizing the residential heating sector in general and residential heating equipment in particular, this study quantitatively defines the theoretical heat and emission recovery capability of the HELPS device. In addition, estimates of the HELPS device's cost to the homeowner, as well as its payback period, were made.

The following are the study's major conclusions:

- The air pollution emissions and energy consumption of equipment used for residential heating are substantial enough that research and development programs aimed at their reduction are fully justified. Many methods have already been explored, but post-combustion control devices have largely been ignored. Techniques capable of concurrently achieving both the energy and emissions goals, such as the HELPS concept, require investigation.
- Residential warm air furnaces are available in both gas- and oil-fired models. Since particulate is emitted only from the latter type, the HELPS device should initially be applied only to oil-fired furnaces in the U.S. When the heat recovery benefits are established on a practical basis, the device may later be applied to gas-fired units.
- Theoretically, the concept will recover most of the waste heat in the flue gas and greatly increase the efficiency of the furnace. On this basis alone, the HELPS concept appears feasible.

- Although the HELPS device will not substantially reduce air pollutant emissions on a nationwide basis, the reduction impact on local, seasonably adjusted emissions could be significant. Controlling emissions from those oil-fired residential furnaces located in densely populated cities will afford added leverage for AQCR's attempting to attain or maintain the National Ambient Air Quality Standards. In addition, most of the emissions from residential furnaces are emitted during only six months of cold weather, a factor which tends to increase the importance of reductions of any magnitude.
- The feasibility of the HELPS device on a cost basis will depend mainly on the cost of fuel oil. As the latter increases, the time required f r the homeowner to recover his investment in the device decreases. Given the current trend in the economics of energy supply, the future of the HELPS concept appears favorable

Based on these facts, the following recommendations can be made:

- The magnitude of the increase in furnace system efficiency depends not only on the performance of the HELPS device itself, but also on the method of using the heat recovered by the scrubbing water. This latter topic must be investigated before the feasibility of the system can be established.
- The effectiveness of the candidate HELPS device on emission cleanup and energy recovery, as well as its retail cost, were calculated and/or estimated by methods based on the design and performance of larger scrubbers. The actual cost-effeciveness of the HELPS device should be determined by prototype development.
- Both of the preceding recommendations can be followed by carrying out the laboratory test program outlined previously in this report. The program is simple in concept, inexpensive, and success-oriented. Completion of this project will be a major step toward determining the feasibility of the HELPS concept.

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APPENDIX A

FURNACE CALCULATIONS

Generalized equation of combustion of #2 fuel oil in residential furnace:

$$C_mH_n + a(1+EA)O_2 + 3.76\ a(1+EA)N_2 + M_a(1+EA)H_2O$$

$$= m\ CO_2 + [n/2 + Ma(1+EA)]\ H_2O + a\ EA\ O_2$$

$$+ 3.76\ a(1+EA)N_2$$

where: m = no. moles C atoms in 1 mole fuel

n = no. mole H atoms in 1 mole fuel

a = (m + n/4)

EA= percent excess air/100

M = Molal humidity of air at T_a and Q percent humidity (or percent saturation)

Assumptions: (1) 60 percent xs air

therefore, EA = 0.6

(2) T_a = 70°F, Q = 65 percent humidity

therefore, from psychrometric chart:

M = 0.0165 moles H_2O/mole dry air

(3) 34 API gravity #2 fuel oil

therefore, $\frac{n}{m} = \frac{MW_C}{MW_H}\left(\frac{\text{wt. \% H}}{\text{wt. \% C}}\right) = \frac{12.01}{1.008}\ (0.1462)$

(from Fuel Oil Manual, Reference 39)

So, n/m = 1.74

Therefore, n/m = 1.74, a/m = 1.435

Combustion products components:

	Moles product/$\frac{1}{m}$ moles fuel	Vol. %
CO_2	1.00	8.77
H_2O	0.908	7.964
O_2	0.861	7.551
N_2	8.633	75.715
TOTAL	11.402	100.0

Now, assume (4) fuel rate = 0.75 gal/hr (equivalent to 100,000 Btu/hr)

Then, for API 34 fuel oil: $\rho = 7.12$ lb/gal

Therefore, fuel rate = (0.75) (7.12) = 5.34 lb/hr

$\Rightarrow MW_{fuel} = MW_C \times m + MW_H \times n$

$\frac{MW_{fuel}}{m} = MW_C + MW_H \times \frac{n}{m} = 12.01 + 1.008\ (1.74)$

$= 13.76$

$MW_{fuel} = 13.76m$ lb/lb mole

Therefore, fuel flow rate = $\frac{5.34 \text{ lb/hr}}{13.76m \text{ lb/lb mole}} = \frac{0.388}{m} \frac{\text{lb moles}}{\text{hr}}$

And, the combustion products flowrates are:

	MW	lb moles/hr	lb/hr
CO_2	44	0.388	17.072
H_2O	18	0.352	6.336
O_2	32	0.334	10.688
N_2	28	3.350	93.8
	28.91		

Summarizing: 4.424 lb moles/hr, 127.9 lb/hr

8.8% CO_2 by volume

lb moles H_2O/hr = 0.352

lb moles dry gas/hr = 4.072

$MW_{dry\ gas} = 29.86$

$$\frac{\text{lb moles } H_2O}{\text{lb mole dry gas}} = 0.0864$$

Now, in order to calculate pollutant concentrations:

Assume (5) emission factors in (lbs/10^3 gal)

From EPA publication AP-42 (Reference 15)

Particulate = 2.5

CO = 5

HC = 1

NO_x = 18

SO_2 = 142S

SO_3 = 2S

} where S = % sulfur in oil

Assume (6) S = 0.3 percent sulfur in oil

Assume (7) 10 percent of NO_x is NO_2 (by volume)

Then, pollutant species flowrates:

Pollutant	MW	10^{-3} lb/hr	10^{-4} lb moles/hr
CO	28	3.75	1.339
NO	30	11.53	3.843
NO_2	46	1.97	0.428
SO_2	64	31.95	4.992
SO_3	80	0.45	0.056
HC	(135)	0.75	0.056
Particulate	–	–	–
		52.275	10.714

=> Total pollutant flowrate = 0.0523 lb/hr, or, 0.0011 lb moles/hr,

Now, in order to calculate the flue gas temperature, we must do a heat balance

Given: sensible heat of reactants = Q_1

heat of reaction = Q_2

heat supplied to home = Q_3

sensible heat out stack = Q_4

and, $Q_1 + Q_2 = Q = Q_3 + Q_4$

where Q is total heat supplied by reaction and by reactants.

Now, assume (8) all reactants @ 70°F.

Therefore, reference state = gases, liquid H_2O + fuel @ 70°F and 1 atm.

Now, $Q_1 = Q_{1a} + Q_{1b} + Q_{1c}$

Where Q_{1a} = sensible heat of fuel = 0

Q_{1b} = sensible heat of dry air = 0

Q_{1c} = heat of water vapor

Then, heat of vaporization @ 70°F = 18,984 Btu/lb mole

$$\Rightarrow \frac{\text{moles } H_2O}{\text{hr}} = M\left(\frac{a}{m}\right)(1 + EA)\ \frac{\text{moles } H_2O}{\frac{1}{m}\text{ moles fuel}} \times 0.388\ \frac{1}{m}\ \frac{\text{moles fuel}}{\text{hr}}$$

$$= (0.0165)\ (1.435)\ (1.6)\ (0.388)$$

$$= 0.0147 \text{ lb moles } H_2O/\text{hr}$$

Therefore, $Q_1 = Q_{1c} = (18{,}984)\ (0.047) = 279$ Btu/hr

Now, Q_2 = (HHV) (fuel rate)

then, for 34 API fuel oil, HHV = 137,310 Btu/gal

and, fuel rate = 0.75 gal/hr

therefore; Q_2 = 102,982 Btu/hr

Now, $Q_1 + Q_2 = Q = 103{,}261$ Btu/hr

and, $Q = Q_3 + Q_4$

Assume (9) efficiency = 80 percent (AGA standard)

therefore, $\frac{Q_4}{Q} = 0.2$

and, $Q_4 = 0.2Q = 20{,}652$ Btu/hr

Now, $Q_4 = \Sigma_i\ n_i\ \Delta h_i$

where n_i = moles product i/hr

Δh_i = change in enthalpy from 70°F to T

Then, $\Delta h_{CO_2} = (h_T - h_{70})_{CO_2}$

$\Delta h_{H_2O} = (h_T - h_{70})_{H_2O} + q_{70}$

$\Delta h_{O_2} = (h_T - h_{70})_{O_2}$

$\Delta h_{N_2} = (h_T - h_{70})_{N_2}$

where q_{70} = heat of vaporization @ 70°F

= 18,984 Btu/lb mole

then, $\Delta h_{H_2O} = (h_T - h_{70})_{H_2O} + 18,984$

Now, must iterate on flue gas temperature:

1st Trial: Try T = 460°F

from tables: $\Delta h_{CO_2} = 3,843$

$\Delta h_{H_2O} = 3,197 + 18,984 = 22,181$

$\Delta h_{O2} = 2,811$

$\Delta h_{N2} = 2,729$

$\Rightarrow \sum_i n_i \Delta h_i = 19,380$ Btu/hr (too low)

2nd Trial: Try T = 480°F

from tables: $\Delta h_{CO_2} = 4,058$

$\Delta h_{H_2O} = 2,266 + 18,984 = 22,350$

$\Delta h_{O_2} = 2,960$

$\Delta h_{N2} = 2,870$

$\Rightarrow \sum_i n_i \Delta h_i = 20,045$ Btu/hr (too low)

3rd Trial: Try T = 500°F

from tables: $\Delta h_{CO_2} = 4,275$

$\Delta h_{H_2O} = 3,536 + 18,984 = 22,520$

$\Delta h_{O_2} = 3,110$

$\Delta h_{N2} = 3,012$

$\Rightarrow \sum_i n_i \Delta h_i = 20{,}715$ Btu/hr (close enough to Q_4)

=> choose combustion products temperature = 500°F

Then, volumetric flow rate $= \left(\frac{\text{lb moles}}{\text{hr}}\right) \frac{(\text{SCF/lb mole})}{(60 \text{ min/hr})}$

$$= \frac{(4.424)\ (359)}{60}$$

$$= 26.47 \text{ SCFM}$$

@ std. conditions: 32°F, 1 atm.

Then, actual volumetric flow rate:

$$(26.47 \text{ SCFM}) \left(\frac{960}{492}\right) = 51.65 \text{ ACFM}$$

Therefore, density $= \frac{\text{lb/hr}}{\text{ACFH}} = \frac{127.9}{(51.65)(60)} = 0.04127 \frac{\text{lb}}{\text{ACF}}$

Summarizing: Flue gas flowrate = 26.47 ACFM

or, 51.65 SCFM

and, $\rho = 0.04127$ lb/ft^3

Flue gas temperature = 500°F

Flue gas pollutant flowrates:

Pollutant	10^{-3} lb/hr
CO	3.75
NO	11.53
NO_2	1.97
SO_2	31.95
SO_3	0.45
HC	0.75
Particulate	1.875

APPENDIX B

HELPS DEVICE BASIC PERFORMANCE CALCULATIONS

Flue gases enter scrubber at following conditions:

$T = 500°F$

H_m = molal humidity = $0.0864 \frac{\text{lb moles } H_2O}{\text{lb moles dry gas}}$

T_{dp} = dew point = 107°F

We want to find the adiabatic saturation temperature (T_{as}) for this gas.

Assume (1) cooling water is available @ $T_W = 50°F$.

Heat balance:

$$C_p \left(T - T_{as}\right) = \left(H_{as} - H_m\right) \left[\lambda_{as} + C_{pw} \left(T_{as} - T_W\right)\right]$$

Where C_p is humid heat capacity @ H_m

H_{as} is molal humidity @ T_{as}

λ_{as} is heat of vaporization @ T_{as}

C_{pw} is heat capcacity of cooling water

Let $C_p\left(T - T_{as}\right) = \sum_i X_i \Delta h_i$

where X_i = moles product i/mole dry gas

Δh_i = change in enthalpy from T_{as} to T

then: $\sum_i X_i \Delta h_i = \left(H_{as} - H_m\right)\left[\lambda_{as} + C_{pw} \left(T_{as} - T_W\right)\right]$

and: $\sum_i X_i \Delta h_i = \left(H_{as} - 0.0864\right) \left[\lambda_{as} + 18 \left(T_{as} - 50\right)\right]$

	X_i	
CO_2	0.0953	T = 500°F
H_2O	0.0864	
O_2	0.0820	
N_2	0.8227	

Must be solved by trial and error:

1st Trial: Try T_{as} = 135°F

then H_{as} = 0.2169

λ_{as} = 18,315

	Δh_i	
CO_2	3,689	$\sum_i x_i \Delta h_i$ = 2,936
H_2O	3,014	
O_2	2,653	RHS = 2,590 (too low)
N_2	2,560	

2nd Trial: Try T_{as} = 137°F

then H_{as} = 0.2311

λ_{as} = 18,294

	Δh_i	
CO_2	3,671	$\sum_i x_i \Delta h_i$ = 2,920
H_2O	2,997	
O_2	2,639	RHS = 2,874 (close enough)
N_2	2,546	

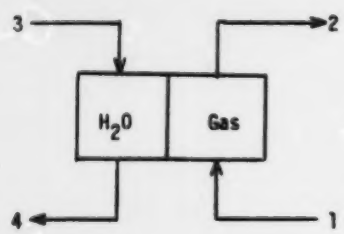
Therefore: T_{as} = 137°F

then, amount of water needed to reduce temperature to 137°F

$$= \left(H_{as} - H_m\right) \times \frac{\text{lb moles dry gas}}{\text{hr}}$$

$$= (0.2311 - 0.0864)(4.072) = 0.5892 \frac{\text{lb moles } H_2O}{\text{hr}}$$

= 10.615 lb H_2O/hr



$$Q_1 + Q_3 = Q_2 + Q_4$$

$$H_1 + H_3 = H_2 + H_4$$

$$Q_1 = C_{p1}\left(T_1 - T_R\right) + H_1\left[\lambda_1 + C_{pw}\left(T_1 - T_R\right)\right]$$

$$Q_2 = C_{p2}\left(T_2 - T_R\right) + H_2\left[\lambda_2 + C_{pw}\left(T_2 - T_R\right)\right]$$

$$Q_3 = H_3\, C_{pw}\left(T_3 - T_R\right)$$

$$Q_4 = H_4\, C_{pw}\left(T_4 - T_R\right)$$

where C_{p1} is mean molal heat capacity of dry gas from T_R to T_1 (Btu/lb mole-°F)

H_1 is molal humidity at T_1 (mole water/mole dry gas)

λ_1 is heat of vaporization at T_1 (Btu/lb mole)

C_{pw} is heat capacity of liquid water (Btu/lb mole-°F)

T_R is reference temperature (°F)

Let $T_R = 77°F$

Also, $T_1 = 137°F$

$H_1 = 0.2311$

$\lambda_1 = 18{,}294$

$C_{pw} = 18.016$

$T_3 = 50°F$

$C_{p1} = 7.171$

Dry gas	x_1
CO_2	0.0953
O_2	0.0820
N_2	0.8227

Therefore, $Q_1 = 4907.8$ Btu/lb mole dry gas

$$Q_3 = -486.43\, H_3$$

$$Q_4 = 18.016\, H_4\left(T_4 - 77\right)$$

$$Q_2 = C_{p2}\left(T_2 - 77\right) + H_2\left[\lambda_2 + 18.016\left(T_2 - 77\right)\right]$$

But $H_4 = H_1 + H_3 - H_2 = 0.2311 + H_3 - H_2$

Substituting into Q_4:

$$Q_4 = 18.016\left(0.2311 + H_3 - H_2\right)\left(T_4 - 77\right)$$

Therefore, heat balance becomes:

$$4907.8 - 486.43\, H_3 = C_{p2}\left(T_2 - 77\right) + H_2\left[\lambda_2 + 18.016\left(T_2 - 77\right)\right] + 18.016\left(0.2311 + H_3 - H_2\right)\left(T_4 - 77\right)$$

This equation now has 3 unknowns in it (specifying T_2, also specifies C_{p2}, H_2, λ_2). The 3 unknowns are T_2, T_4, and H_3.

T_2	λ_2	H_2	C_{p2}	Q_2
60	1 ,085	0.0184	7.134	224.25
70	18,984	0.0262	7.139	444.10
80	18,882	0.0370	7.143	722.06
90	18,780	0.0517	7.147	1,075.95
100	18,678	0.0716	7.151	1,531.49

$$4{,}907.8 - 486.43\ H_3 = Q_2 + 18.016\ (0.2311 + H_3 = H_2)\ (T_4 - 77)$$

For $T_2 = 60°F$

$$4{,}907.8 - 486.43\ H_3 = 224.25 + 18.016\ (H_3 + 0.2127)\ (T_4 - 77)$$

$$\text{or, } 4{,}683.6 = (T_4 - 77)(18.016\ H_3 + 3.832) + 486.43\ H_3$$

$$H_3 = \frac{4{,}978.7 - 3.832\ T_4}{18.016\ T_4 - 900.80} = \frac{276.35 - 0.2127\ T_4}{T_4 - 50}$$

For $T_2 = 70°F$

$$4{,}907.8 - 486.43\ H_3 = 444.10 + 18.016\ (H_3 + 0.2049)\ (T_4 - 77)$$

$$\text{or, } 4{,}463.7 = (T_4 - 77)(18.016\ H_3 + 3.691) + 486.43\ H_3$$

$$H_3 = \frac{4{,}747.9 - 3.691\ T_4}{18.016\ T_4 - 900.80} = \frac{263.54 - 0.2049\ T_4}{T_4 - 50}$$

For $T_2 = 80°F$

$$4{,}907.8 - 486.43\ H_3 = 722.06 + 18.016\ (H_3 + 0.1941)\ (T_4 - 77)$$

$$\text{or, } 4{,}185.7 = (T_4 - 77)(18.016\ H_3 + 3.497) + 486.43\ H_3$$

$$H_3 = \frac{4{,}454.9 - 3.497\ T_4}{18.016\ T_4 - 900.8} = \frac{247.28 - 0.1941\ T_4}{T_4 - 50}$$

For $T_2 = 90°F$

$$H_3 = \frac{226.51 - 0.1794\ T_4}{T_4 - 50}$$

For T_2 = 100°F

$$H_3 = \frac{199.69 - 0.1595\ T_4}{T_4 - 50}$$

For any T_2:

$$H_3 = \frac{A - (0.2311 - H_2)\ T_4}{T_4 - 50}$$

$$\text{where } A = \left(\frac{4{,}907.8 - Q_2}{18.016}\right) + 77(0.2311 - H_2)$$

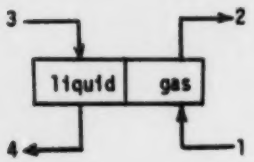
In summary:

1. Amount of water needed to saturate 500°F gas:

$$0.2311 - 0.0864 = 0.1447 \frac{\text{lb moles } H_2O}{\text{lb mole dry gas.}}$$

2. To convert from lb moles H_2O/lb mole dry gas to GPM water, multiply by 0.1468 assuming a density of 8.33 lb/gal.

3. Molal humidities (H) are total water/mole dry gas. They include the water needed for saturation. $H_4 = (H_1 - H_2) + H_3 = 0.2311 - H_2 + H_3$.

4. 

T_1 = 500°F

T_3 = 50°F

5. For T_2 = 60, 70, 80, 90, 100°F, values for H_1, H_2, H_3, H_4 are tabulated in Table B-1.

6. The performance of the HELPS device is shown in Figure B-1.

Now we can calculate the heat recovery properties. Given, gas flow rate = 127.9 lb/hr or 51.65 ft^3/min

Assume, T_2 = 80°F, T_4 = 120°F, then inlet water flow rate = 245.4 lb/hr or 0.49 GPM and, outlet water flow rate = 249.0 lb/hr

So, heat transferred = $Q_T = C_{pw}\left[m_o(T_4 - T_R) - m_i\ (T_3 - T_R)\right]$

where C_{pw} is heat capacity of water

m_0 is outlet water flow rate

m_1 is inlet water flow rate

T_3 is inlet water temperature

T_4 is outlet water temperature

T_R is reference temperature (70°F)

Then, $Q_T = 1.0 \left[249(50) - 245.4\ (-20)\right] = 17{,}358$ Btu/hr.

Original enthalpy of flue gas = 20,652 Btu/hr.

$\underline{\text{Net Heat Recovery}} = \frac{17{,}358}{20{,}652} = 84\%$

Increases overall efficiency of system to almost 97 percent (furnace + heat recovery unit.)

The above temperatures will be used to design our heat recovery unit.

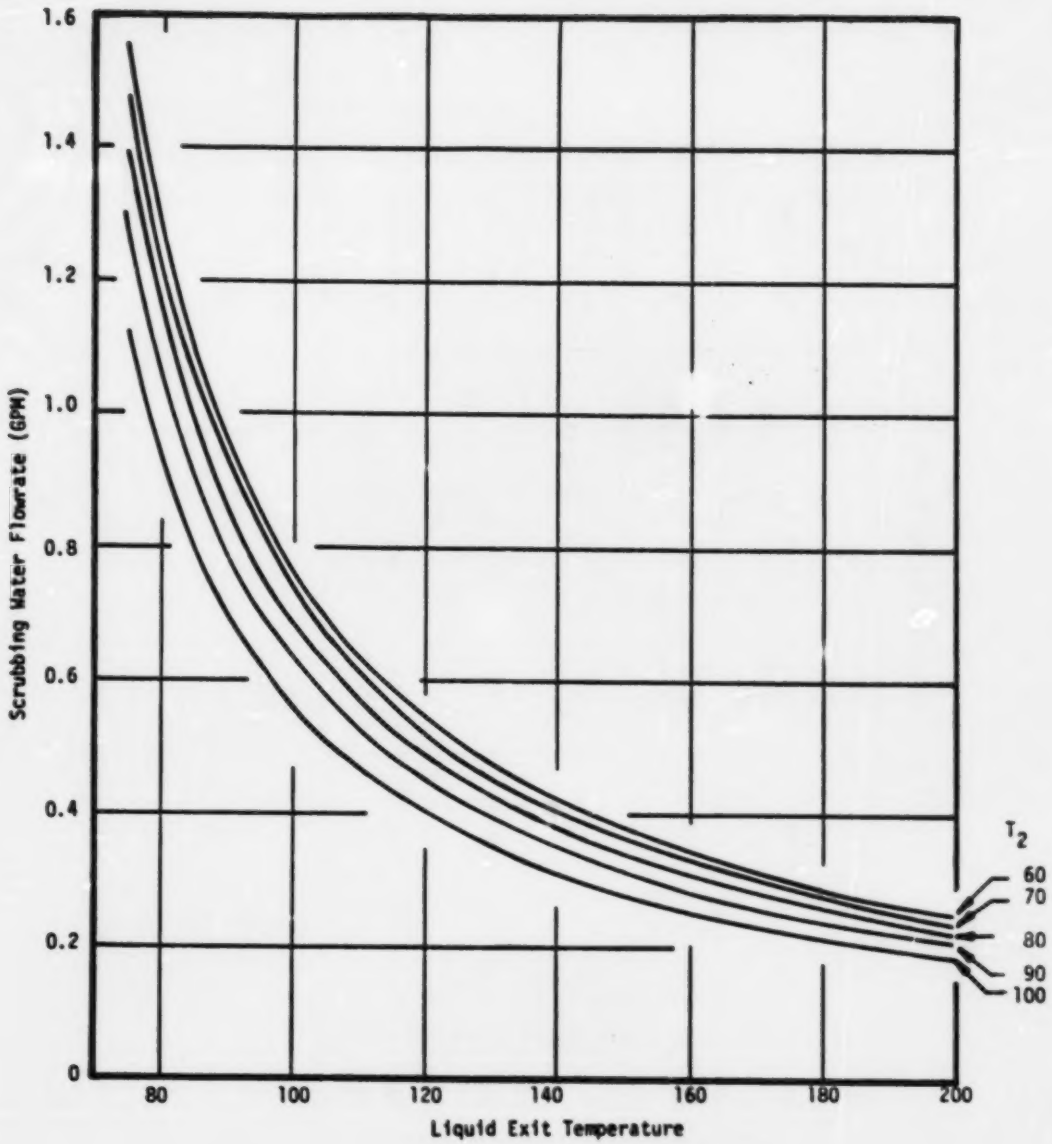


Figure B-1. HELPS device performance curves.

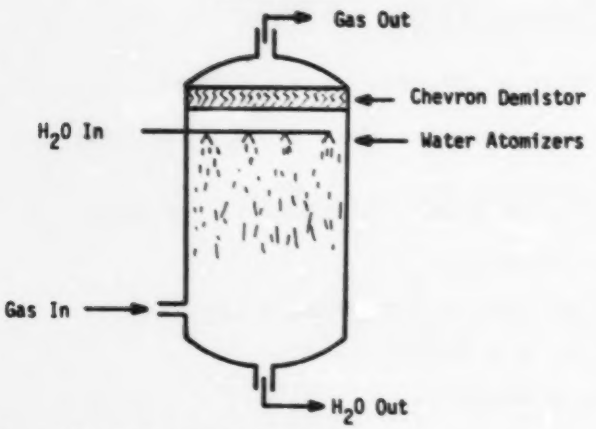
TABLE B-1. T_2 VERSUS H_1, H_2, H_3, H_4

T_2	H_2	H_1	H_3	H_4
60	0.0184	0.0864	$\left(\frac{276.35 - 0.2127\ T_4}{T_4 - 50}\right) + 0.1447$	$H_3 + 0.0680$
70	0.0262	0.0864	$\left(\frac{263.54 - 0.2049\ T_4}{T_4 - 50}\right) + 0.1447$	$H_3 + 0.0602$
80	0.0370	0.0864	$\left(\frac{247.28 - 0.1941\ T_4}{T_4 - 50}\right) + 0.1447$	$H_3 + 0.0494$
90	0.0517	0.0864	$\left(\frac{226.51 - 0.1794\ T_4}{T_4 - 50}\right) + 0.1447$	$H_3 + 0.0347$
100	0.0716	0.0864	$\left(\frac{199.69 - 0.1595\ T_4}{T_4 - 50}\right) + 0.1447$	$H_3 + 0.0148$

APPENDIX C

HELPS DEVICE DESIGN CALCULATIONS

Spray Tower



Gas Flow rate in = 127.9 lb/hr or 51.65 ft^3/min

Gas Temp. in = 500°F

Gas Temp. out = 80°F

Water Flow rate in = 245.4 lb/hr or 0.49 GPM

Water Temp in = 50°F

Water Temp out = 120°F

Assume (1) D = 10 in. = diameter of chamber

therefore, $A = \frac{\pi}{4} D^2 = 0.545$ ft^2

and, $\bar{u}_G = 1.58$ ft/sec = average gas velocity

$$G = \frac{127.9}{A} = 234.7 \text{ lb/hr ft}^2$$

$$L = \frac{245.4}{A} = 450.3 \text{ lb/hr ft}^2$$

Assume (2) d = 200 μ = average droplet diameter

then, $V_d = \frac{\pi}{6} d^3$ = drop volume

No. drops/sec = $\frac{\dot{m}_L}{\rho_L V_d}$

where $\dot{m}_L$ is mass flow rate in lb/sec

ρ_L is density of water

$A_d = \pi d^2$ = drop surface area

therefore, interfacial surface area/sec = $\frac{\dot{m}_L}{\rho_L V_d} A_d = \frac{\dot{m}_L}{\rho_L} \frac{6}{d}$

$= \frac{245.4}{(3,600)(62.3)} \frac{6}{6.56\times10^{-4}} = 10$ ft²/sec

Terminal velocity of 200 μ drop = u_t = 2.17 ft/sec

Velocity of drop relative to walls = $u_t - \bar{u}_G$ = 0.59 ft/sec.

Therefore, $\frac{\text{Interfacial area}}{\text{volume of bed}} = a = \frac{10 \text{ ft}^2/\text{sec}}{0.545 \text{ ft}^2} \frac{1}{0.59 \text{ ft/sec}}$

or, $a = 31.1$ ft²/ft³

Assume (3) effective area = 10 percent of actual area, so:

$a_e = 0.1a = 3.11$ ft²/ft³

Now, the gas properties are:

@ T = 200°F

$\mu_G = 2\times10^{-4}$ gm/cm sec

$\rho_G = 0.001$ gm/cm³

$K_G = 0.014$ Btu/hr ft°F

$C_{p_G} = 0.23$ Btu/lb°F

therefore, $\frac{C_p \mu}{k} = Pr = 0.8$

h = heat transfer coefficient

$= \frac{K_G}{d}\left(2 + 0.6\ Re_d^{1/2}\ Pr^{1/3}\right)$

$Re_d = \frac{d\ u_t\ \rho_G}{\mu_G} = 6.6$; Pr = 0.8

therefore, $h = \frac{0.014}{6.56\times10^{-4}}$ (3.43) = 73 Btu/hr ft²°F

Now, $Q_T = (ha_e)\ V\ \Delta T_{lm}$

where Q_T is heat transferred

V is volume of chamber

ΔT_{lm} is log-mean temperature difference.

Q_T = 17,358 Btu/hr

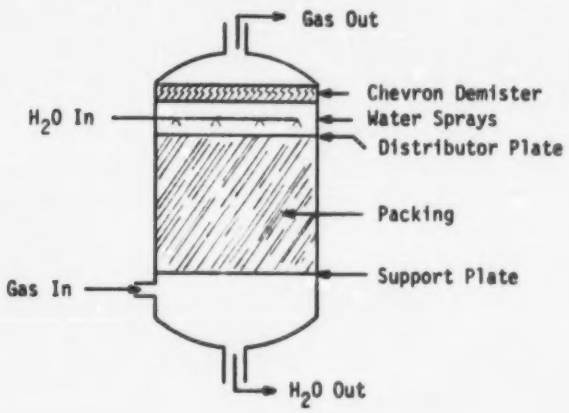
$$\Delta T_{lm} = \frac{(500-120) - (80-50)}{\ln \frac{500-120}{80-50}} = 138°F$$

h_{a_e} = (73)(3.11) Btu/hr ft³°F

therefore, $V = \frac{Q_T}{h_{a_e} \Delta T_{lm}} = \frac{17,358}{(73)(3.11)(138)} = 0.554$ ft³

But A = 0.545 ft², so, $Z = \frac{V}{A} = 1.02$ ft and, ΔP gas ≈ 1" W.C.

Packed Tower



Assume (1) packing is 1/4" Ceramic Berl Saddles

therefore, a = 274 ft²/ft³

and a_e = 0.1a = 27.4 ft²/ft³

Assume (2) same diameter as before (10")

also, same flow rates and temperatures

$$R_e = \frac{G}{a\psi\mu_G} = \frac{234.7}{(274)(0.8)(0.0484)} = 22.1$$

where ψ = shape factor for Berl saddles

Now $h = 0.91\ R_e^{-0.51} \psi\ C_{p_G}\ G\ Pr^{-2/3}$

$= 0.91\ (22.1)^{-0.51} (0.8)(0.23)(234.7)(0.8)^{-2/3}$

= 9.4 Btu/hr ft²°F

Now, $V = \frac{Q_T}{h a_e \Delta T_{lm}}$

$= \frac{17,358}{(9.4)(27.4)(138)} = 0.488 \text{ ft}^3$

and, $Z = \frac{V}{A} = 0.9 \text{ ft}$

$\Delta P_{gas} = 1 \text{ in. } H_2O$

APPENDIX D

HELPS COST CALCULATIONS

Capital Cost (Estimate)

Capital cost = parts cost and installation cost = $200 + $25 = $225

Annual Costs

- Water cost

  Given: Water cost = 0.005 $/gal (San Francisco Bay Area)

  Residential energy use = 1040 therm/yr (Reference 40)

  HELPS total water use = 0.5 gal/min

  Makeup water/total water use = 0.1

  Furnace heat release rate = 100,000 Btu/hr

  Then, additional water cost due to HELPS device

  = (1040 therms/yr)(100,000 Btu/therm)(1/100,000 hr/Btu)(60 min/hr)
  (0.5 gal/min)(0.1)(0.005 $/gal)

  = 16 $/yr

- Electricity cost

  Given: No increased water pressurizing cost; use 40 psig house water pressure

  Fan power = 1/8 HP = 93 watts = 0.093 KW

  Electricity cost = 0.03 $/KWhr

  Then, additional electricity cost due to HELPS device

  = (1040 therms/yr)(100,000 Btu/therm)(1/100,000 hr/Btu)(0.093 KW)(0.03 $/KWhr)

  = 3 $/yr

- Operating cost

  Annual operating cost = water cost + electricity cost = 16 + 3 = 19 $/yr

- Maintenance cost

  Annual maintenance cost (parts only) = 5 $/yr

Example Fuel Savings Calculations

Given: Fuel cost = 0.45 $/gal

Fuel heating value = 138,000 Btu/gal

Furnace efficiency increase due to HELPS = 0.17

Then, annual savings in fuel due to HELPS device

= (0.45 $/gal)(1040 therms/yr)(100,000 Btu/therm)(1/138,000 gal/Btu)(0.17/0.80)

= 72 $/yr

Example Payback Period Calculation

Given: Fuel cost = 0.45 $/gal

Fuel savings = 72 $/yr

Then, savings per year

= Fuel savings - operating and maintenance costs

= 72 - 24 = 48 $/yr

And, amount

= capital costs/savings per year

= 225/48 = 4.69

Then, interpolating in Table 5-6, the time required to break even on the cost of the HELPS device (payback period) = 6.2 years

APPENDIX E

METRIC SYSTEM CONVERSION FACTORS

Although EPA's policy is to use the metric system in all of its documentation, certain non-metric units are used in this report for convenience. Readers more familiar with the metric system may use the following to convert to that system:

Non-Metric Unit	Multiplied By	Yield Metric Unit
in.	2.540	cm
ft	0.3048	m
ft^2	9.3×10^{-2}	m^2
ft^3	28.317	liter
gal	3.785	liter
lb	0.454	kg
°F	5/9 (°F-32)	°C
Btu	1.055×10^3	joule
Btu/ft^3	37.256	joule/liter